Bulletin

of

The Geological Society of America

VOLUME 67 January 1956 NUMBER 1

CONTENTS

	Pages
Geophysical investigations in the emerged and submerged Atlantic Coastal Plain. Part X: Continental Slope and Continental Rise south of the Grand Banks. By Charles R. Bentley and J. Lamar Worzel	1–18
Stratigraphic sequence in the Eagle Rock volcanic area near American Falls, Idaho. By Harold T. Stearns and Andrei Isotoff	19–34
Uranium-lead method of age determination. Part I: Lake Athabasca problem. By Walter R. Eckelmann and J. Laurence Kulp	35–54
Ordovician limestones in the western anticlines of the Appalachians in West Virginia and Virginia northeast of the New River. By Marshall Kay	55–106
Post-Laramie stratigraphic correlations in the Denver Basin, Colorado. By Stanley O. Reichert	107–112
Short Notes	
United Nations Conference on the Peaceful Uses of Atomic Energy: Geological aspects. By Paul F. Kerr	113–120
Drakensberg scarp of South Africa: a clarification. By Lester C. King	121–122
Lead and sulfur isotopic abundances in Mississippi Valley galenas. By J. L. Kulp, G. L. Bate, W. U. Ault, and H. W. Feely	123–124
Terminology for stratification in sedimentary rocks. By John Bokman	125–126

Subscription $15.00 per year.

Printing Office: Mt. Royal & Guilford Aves., Baltimore 2, Md.

Communications for publications should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117 Street, New York, N. Y.

Please give notice of change of address 4 weeks in advance. Claims for nonreceipt of the Bulletin of a given month must be sent to the Secretary of the Society before the end of the second succeeding month.

Entered as second-class matter at the Post Office at Baltimore, Md.,
under the Act of Congress of July 16, 1894.
Accepted for mailing at special rate of postage provided for in Section 1103
Act of October 3, 1917, authorized on July 8, 1918.

PAPERS IN PRESS FOR FORTHCOMING ISSUES

Geology of the Blue Ridge near Harpers Ferry, West Virginia. By Richard P. Nickelsen

Interpretation of the Configuration of the Aleutian Ridge. By Olcott Gates and William Gib

Mineralogy and Petrology of the Sittampundi Complex, Salem District, Madras State, In
By A. P. Subramaniam

Petrology and Weathering of the Iron Dike, Boulder and Larimer Counties, Colorado.
Ernest E. Wahlstrom

Direct Radiometric Measurement of the Uranium and Thorium Series in Equilibrium by Gam
Ray Scintillation. By P. M. Hurley

Late Wisconsin Chronology of the Lake Michigan Basin Correlated with Pollen Studies.
James H. Zumberge and John E. Potzger

Upper Croixian Stratigraphy, Upper Mississippi Valley. By C. A. Nelson

Pegmatites in West Greenland. By Hans Ramberg

Structure of Lopoliths. By H. D. B. Wilson

Nickelsen

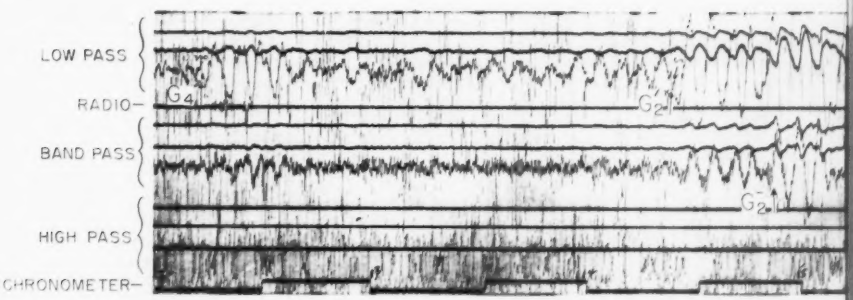
William Gibson

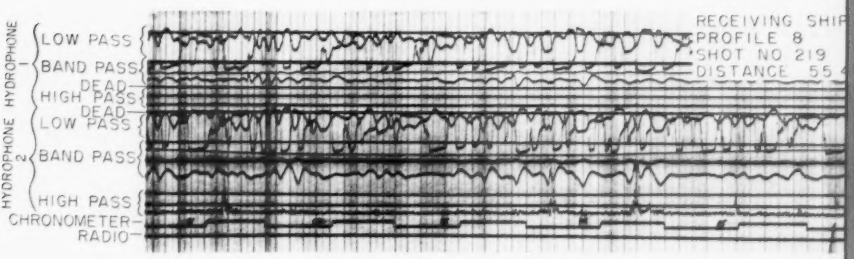
s State, India.

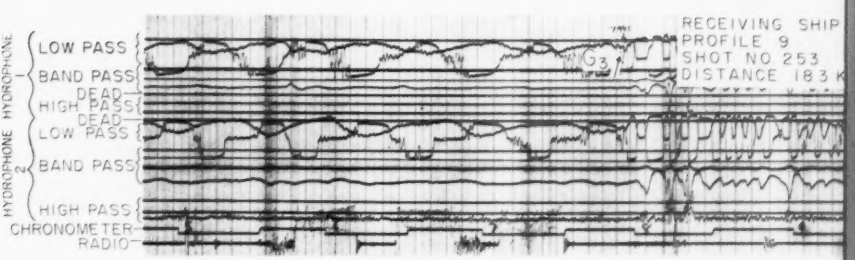
Colorado. By

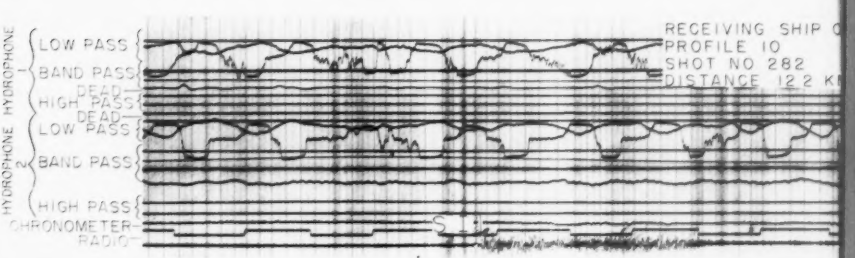
rium by Gamma-

n Studies. By

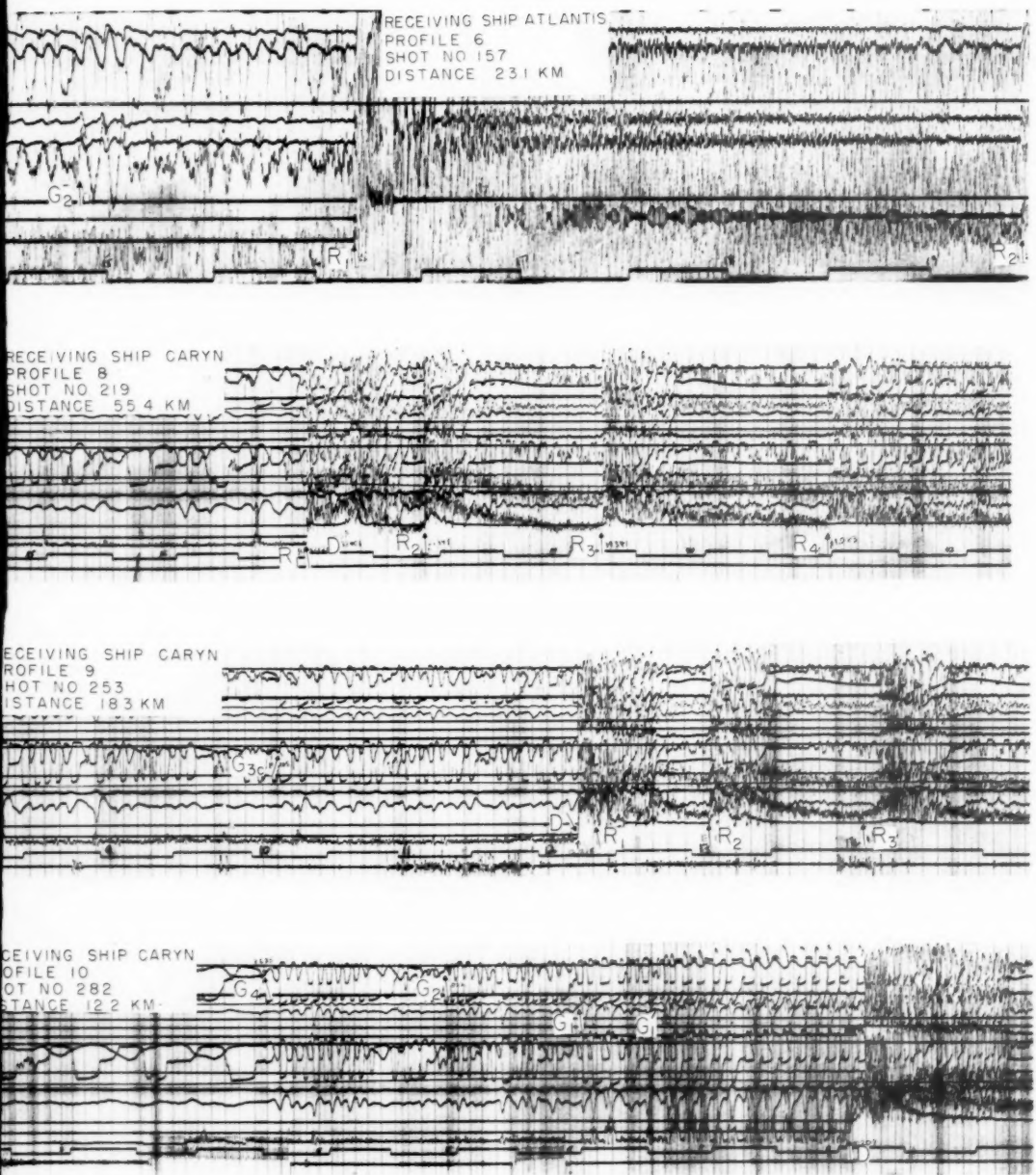

LOW PASS
RADIO
BAND PASS
HIGH PASS
CHRONOMETER
G4
G2
G2


HYDROPHONE 1
HYDROPHONE 2
LOW PASS
BAND PASS
DEAD
HIGH PASS
DEAD
LOW PASS
BAND PASS
HIGH PASS
CHRONOMETER
RADIO
RECEIVING SHIP
PROFILE 8
SHOT NO 219
DISTANCE 55


HYDROPHONE 1
HYDROPHONE 2
LOW PASS
BAND PASS
DEAD
HIGH PASS
DEAD
LOW PASS
BAND PASS
HIGH PASS
CHRONOMETER
RADIO
G3
RECEIVING SHIP
PROFILE 9
SHOT NO 253
DISTANCE 183 K


HYDROPHONE 1
HYDROPHONE 2
LOW PASS
BAND PASS
DEAD
HIGH PASS
DEAD
LOW PASS
BAND PASS
HIGH PASS
CHRONOMETER
RADIO
RECEIVING SHIP
PROFILE 10
SHOT NO 282
DISTANCE 122 K

SAMPLE RE



SAMPLE REFRACTION RECORDS

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 67, PP. 1-18, 8 FIGS., 1 PL. JANUARY 1956

GEOPHYSICAL INVESTIGATIONS IN THE EMERGED AND SUBMERGED ATLANTIC COASTAL PLAIN

PART X: CONTINENTAL SLOPE AND CONTINENTAL RISE SOUTH OF THE GRAND BANKS

BY CHARLES R. BENTLEY AND J. LAMAR WORZEL

ABSTRACT

Seismic-refraction profiles shot on the continental rise and slope south of the Grand Banks show great sediment thickness which reaches a maximum of nearly 10 km about 90 km south of the 100-fathom curve and thins rapidly under the banks. Three sediment layers are present, with average velocities of 1.83, 2.47, and 3.97 km per second, the highest velocity layer constituting the major portion of the column. The basement is thickest under the south edge of the continental shelf, thinning to 2 or 3 km to the north and to the south. Its velocity averages 5.77 km/sec except on the southernmost profile where it is 6.70 km/sec. Sub-basement is reached on the three southernmost profiles at an average depth of about 13 km, the velocity decreasing from south to north from 7.76 km/sec to 7.24 km/sec.

CONTENTS

TEXT

	Page
Introduction	1
Acknowledgments	1
Equipment	2
Method of investigation	2
Interpretation of data	3
Travel-time data and results	4
General	4
Profile 6	4
Profile 7	5
Profile 8	5
Profile 9	5
Profile 10	14
Discussion	15
Geological implications	15
References cited	17

ILLUSTRATIONS

Figure	Page
1. Location of refraction profiles	2
2. Travel-time curves and section, profile 6	9
3. Travel-time curves and section, profile 7	10
4. Travel-time curves and section, profile 8	11
5. Travel-time curves and section, profile 9	12
6. Travel-time curves and section, profile 10	13
7. Ray diagrams of reflected refracted rays	14
8. Seismic and geologic sections	16

Plate	Facing page
1. Sample refraction records	1

TABLES

Table	Page
1. Apparent velocities and time intercepts	6
2. True velocities and thicknesses	8

INTRODUCTION

During the summer of 1951, 19 refraction profiles were made on ATLANTIS 173 and CARYN 25 cruises along tracks from Woods Hole, Massachusetts, to Bermuda, Bermuda to Argentia, Newfoundland, and along the Grand Banks, as a part of the program of seismic investigation of Atlantic continental margins started in 1935 by Maurice Ewing and continued since that time under his direction. The present paper discusses the results of profiles 6, 7, 8, 9, and 10 which form a line across the continental rise and continental slope south of Cape St. Mary on the Avalon Peninsula, Newfoundland (Fig. 1).

ACKNOWLEDGMENTS

The research was carried out under contracts N6-onr-27113 and N6-onr-27124 with the office of Naval Research, and NObsr 43355 with the Bureau of Ships, of the Department of the Navy. The Woods Hole Oceanographic

Institution kindly made available the Research Vessels ATLANTIS and CARYN. The co-operation and help of Captains John F. Pike of the CARYN and Adrian K. Lane of the ATLANTIS and their officers and crew is gratefully acknowledged. The largest part of the equipment was made available by Columbia University.

The generous assistance of the members of the scientific parties, Charles Drake, Walter Beckmann, Maurice Major, John Northrop, David Warren, James Dorman, Leonard Johnson, Patrick Coyle and Duncan Foster Jr., without which the field work would have been impossible, is greatly appreciated.

Our thanks also goes to the Atlantic Refining Company for providing the oscillograph which was used on the CARYN throughout the cruise.

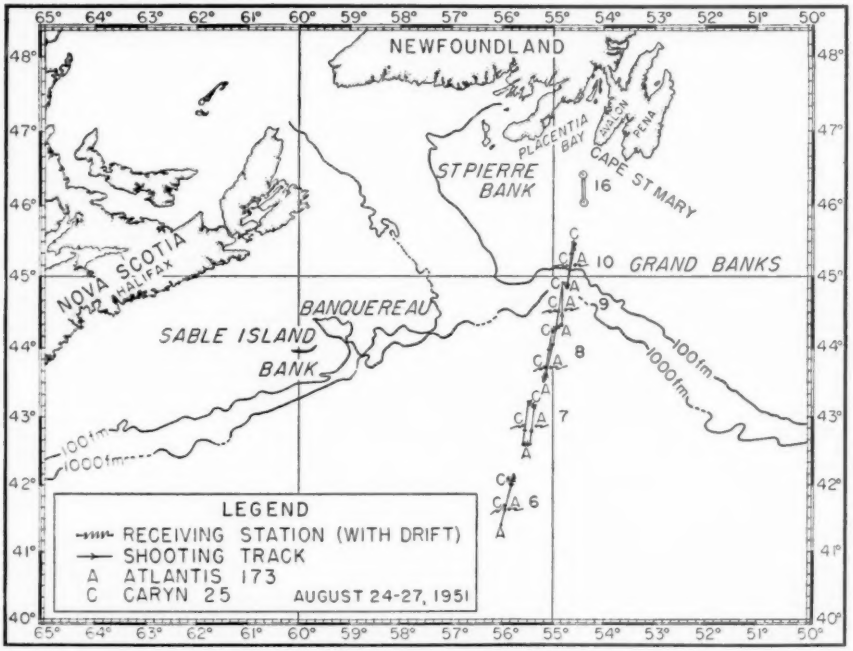


FIGURE 1.—LOCATION OF REFRACTION PROFILES

EQUIPMENT

On both the ATLANTIS and the CARYN two hydrophones were used with two separate amplifiers. The hydrophones were Brush De-Development Company type AX58; the amplifiers were of the three-channel type developed by G. H. Sutton (1952). The half-power points for the low, medium, and high frequency channels of the amplifier are 3.5 and 135 cycles/sec, 30 and 250 cycles/sec, and 620 and 14,000 cycles/sec, respectively. A Century Geophysical Corporation recording oscillograph was used on the ATLANTIS and an Atlantis Refining Company recording oscillography on the CARYN. Shot instants were picked up on each ship by its echo-sounder sound head. The output of the sounder was fed to an earphone held against the microphone of a Navy model TCS radio transmitter.

METHOD OF INVESTIGATION

Our standard method of shooting reversed seismic refraction profiles was employed, and is summarized here. The ATLANTIS hove to on receiving station recording shots fired by the CARYN as she proceeded north. After the last shot the CARYN hove to and recorded the ATLANTIS' shots as she approached. Thus each

line was covered twice, once in each direction, the point of maximum distance on each leg forming the receiving point on the other leg. (Officer *et al.*, 1952, p. 780–781, give further details.)

Charges ranged from ½ to 150 pounds of TNT, and all were fired by a burning fuse. Each profile was extended as far as satisfactory ground arrivals could be obtained, varying between 50 and 75 km in length.

A continuous depth record made by the shooting ship was essential in order to properly correct for the large bottom relief. The echo time beneath the shooting ship was recorded on each shot, giving the depth at the shot points with more accuracy than was available from the echo sounder.

Bathythermograph observations were made hourly while under way by the ATLANTIS, and at the start and end of each receiving station by the CARYN.

INTERPRETATION OF DATA

The method of interpretation used was that of Ewing *et al.* (1939, p. 262–267). The assumptions underlying this method are that:

(1) Each layer is bounded top and bottom by planes and transmits seismic waves at a constant velocity.

(2) At the interface between two layers the path of a seismic wave is determined by Snell's law.

(3) A wave travelling in any layer with velocity V, and incident upon the surface of the layer at an angle α with the normal, has an apparent velocity V/sin α along the surface.

(4) Any travel time will be unchanged if shot point and recording point are interchanged.

If these assumptions are upheld, the plot of travel time of the seismic waves versus the distance between shot and receiving point will consist of a series of straight lines, with one line corresponding to each seismic layer, or, for a reversed profile, one line in each direction for each layer. The reciprocal of the slope of any line gives the apparent velocity in the corresponding layer in that direction; if the apparent velocities in both directions are known, the true velocity and the layer slope can be computed. The time intercept of a line extended back to zero distance affords a measure of the depth to the corresponding layer.

From assumption (4) and the method by which these reversed profiles are made it follows that the travel time through any layer must be the same in either direction when the ships are at maximum separation; the corresponding points on the travel-time curve are known as *reverse points*. Given a line in one direction, The equality of the reverse points enables one to draw a line in the reverse direction with only one observed point.

It is often possible to get certain identification of seismic impulses only from first arrivals. For this reason, and because the reconnaissance nature of this work prevents detailed examination of each layer, control over the various lines rarely extends to more than a fraction of the total profile length. An extension of these segments to the full reverse distance and a comparison of corresponding reverse points provides a check upon the validity of assumption (1). Good agreement indicates that this assumption was valid.

Sometimes arrivals through a layer are obtained in only one direction of a reversed profile owing to poor records, improper spacing of shots, misfires, etc., or because the layer is *masked, i.e.* so thin and having such velocity contrasts with the adjacent layers that it cannot be observed by first arrivals. In this case the reverse line is drawn through the reverse point according to an assumption either of the true velocity of the layer or of the dip of its surface, the other thus being determined.

On most records a ground wave, a direct water wave, and two reflected water waves were read. In addition to the first arrival, later ground waves were read when possible, these being of particular value in determining the semiconsolidated sediment lines. Plate 1 shows some sample records. G_x indicates an arrival through the x^{th} layer from the top, excluding the water, R_x a wave reflected x times from the ocean bottom, D the direct water wave, and S.I. the shot instant. The arrivals labeled G_2' and G_1' on shots 157 and 282 are explained under Profile 6 and Profile 10 respectively.

Direct water waves were obtained on all shots except those at a distance greater than 15 km on profile 6. Their presence on the other

profiles was due to the existence of a surface sound channel caused by a temperature inversion at a depth of 200–300 feet. The minimum velocity in the sound channel was taken as the velocity, c_0, of the direct wave for these profiles. As a check on this assumption, a direct water-wave travel time (D) was computed from the first reflection time (R_1) and the depth of water (h) by the formula $D = \frac{\bar{c}_v}{c_0}\sqrt{R_1^2 - 4h^2}$, where $\bar{c}_v$ is the average vertical sound velocity in the water taken from the British Admiralty tables of the velocity of sound in sea water for this region. This computed value was found to agree, within the limits of error, with that observed, justifying the original choice of c_0. The sound-channel velocity was about 1 per cent less than the average vertical velocity with the result that on some distant shots the first reflection arrived before the direct wave (Pl. 1, shot 219). For those shots on profile 6 lacking a direct water wave, the value of D computed from the first reflection time by the given equation was used.

Corrections were made to all shots for the depth of shot and hydrophone, and distance of the shot from the shooting ship. The shot depth was determined from the length of time over the side and sinking-rate curves of Officer and Wuenschel (1951, Figs. 3–9).

Corrections also had to be made on all profiles for the effect of the submarine topography. On profiles 6, 7, and 8, where the variations were small and the semiconsolidated layer was thick, the irregularities were assumed to be a reflection of the surface of the semiconsolidated layer. On profiles 9 and 10, where the relief was much greater and the overlying layers thinner, the topography was assumed to be in the consolidated sediment layer. These choices seemed to minimize the scatter of the points on the travel-time curves.

Error calculations were made on all refraction lines having three or more points, using the Student's *t* distribution (*e.g.* Hoel, 1947, p. 148). A confidence interval of 68 per cent was used by the authors, to correspond to the standard error of least squares.

Travel-Time Data and Results

General

The travel-time curves are presented in Figures 2–6. The horizontal scale on each is in direct water-wave travel time; the distance in kilometers is shown on the corresponding seismic section which is drawn, with no vertical exaggeration, beneath each travel-time plot. A travel-time equation is given for each refraction line in the form $T = I + X/V$ where T = travel time in seconds, I = time intercept in seconds, X = distance in kilometers, and V = apparent velocity in km/sec. R_1 and R_2 indicate the first and second reflection curves, respectively, and D indicates the direct water-wave lines.

For convenience in reference, the various layers have been given names; these have, however, no strict geologic significance. The basement has been so named because it can be definitely correlated with the basement on land. The layers above are presumably sediment of different degrees of consolidation, hence have been called unconsolidated, semiconsolidated, and consolidated sediment. Any layer below the basement has been called simply sub-basement, regardless of its velocity or relation to sub-basement or other profiles. Subscripts U, S, C, B, N in the travel-time equation indicate unconsolidated sediment, semiconsolidated sediment, consolidated sediment, basement, and sub-basement, respectively.

Table 1 lists the velocities and time intercepts observed on each profile; Table 2 gives the computed velocities and layer thicknesses.

Profile 6 (Fig. 2)

Since no arrivals were obtained from it, the unconsolidated sediment layer was assumed to have a velocity of 1.79 km/sec to be in accord with the values observed for profiles 7 and 8. Second arrivals determine fairly good lines for the semiconsolidated layer on each end of the profile, but the lines do not reverse, indicating a change of velocity between the two ends. The slope taken for the surface of this layer is one found by trial and error to agree with the observed intercepts. Another set of second

arrivals (G_2; *see* Pl. 1, shot 157) form a line with slightly higher velocity than that of the semiconsolidated layer, falling slightly below it, and tangent to the first reflection curve. The arrivals are stronger on later records, and the phase does not appear on shot 155 where it should be the first arrival. No satisfactory explanation is known for this line. The low intercept precludes the possibility of its representing either another sediment layer or a set of shear arrivals. The higher velocity of the line and the fact that the amplitude of the phase increases with distance prevent an explanation by means of a low velocity layer within the sediment.

The consolidated sediment layer is determined by only two points from CARYN receiving and one fairly good point from ATLANTIS receiving, however, the velocity agrees well with that on the other profiles. The basement and sub-basement are both well determined by reversed first arrival lines.

Profile 7 (Fig. 3)

Owing to difficulties in recording shot instants on the CARYN, only two good records were obtained on that ship. These give a reverse for the sub-basement line, but all other lines are unreversed. Therefore reverse lines were assumed such that the thickness of the three top layers at the north (CARYN) end of the profile fitted with those at the south end of profile 8. The consolidated-sediment line is again poorly determined, with only one first arrival and two rather weak second arrivals; however the velocity thus found is in good agreement with the other profiles.

The sub-basement line shows good evidence of structure on a buried surface. Shots 188, 189, and 190 form a line with apparent velocity less than that of the average line, whereas 185, 186, and 187 give a line with apparent velocity greater than the average. This indicates a humplike structure such as is shown in the section by the dotted lines. However it is impossible to say upon which surface this structure should be. A relief of 2 km on any one of the three lowest surfaces would equally well explain the observed deviation of the points.

Good second arrivals on shots 186, 187, 188, and 189 form a good line about 6 seconds above the sub-basement line in the ATLANTIS receiving direction, and nearly parallel to it. The theoretical line is drawn for bottom-reflected refracted arrivals (G_{3b}), *i.e.* those which reflect once off the ocean floor and ocean surface and then follow a normal refraction path (Fig. 7a). Despite the considerable deviation from the theoretical line, the arrivals are believed to be of this type.

Profile 8 (Fig. 4)

All velocites are determined in at least one direction. The unconsolidated layer is fixed by two good second arrivals and the condition of tangency to the first reflection curve. The semiconsolidated line is well determined by good second arrivals on ATLANTIS records and one first arrival on the CARYN, the consolidated sediment line by first arrivals in both directions. The next layer determined by the points has a velocity, 7.24 km/sec, that is much too high to correlate with the basement velocities found in the profiles on either side. This would mean that the basement layer would have to pinch out north from profile 7 and also south from profile 9. It seems more reasonable to assume that the basement merely thins beneath this profile, hence a masked layer is assumed with a velocity of 5.87 km/sec and with upper and lower surfaces parallel. A computed maximum thickness of 2.79 km for this layer has been included in the section.

The sub-basement line is very well determined.

Of interest is the line of shear-wave arrivals through the consolidated sediment (G_{3s}). That these arrivals are not compressional waves through another layer is shown by the large intercept of the line which would produce a negative thickness for such a layer. See Ewing *et al.*, 1954, p. 32). The ratio of compressional to shear velocity is 1.69 as compared with a theoretical value of 1.73 assuming Poisson's ratio to be .25.

Profile 9 (Fig. 5)

Both unconsolidated and semiconsolidated sediment lines are determined by second

TABLE 1.—APPARENT VELOCITIES AND TIME INTERCEPTS

Apparent Velocities

Profile	Unconsolidated sediment		Semiconsolidated sediment		Consolidated sediment		Basement		Sub-basement	
	km/sec	ft/sec	km/sec	ft/sec	km/sec	ft/sec	km/sec	ft/sec	km/sec	ft/sec
6N	(1.78)*	(5,840)	2.66 ± .02	8,720 ± 60	3.84	12,600	6.68 ± .15	21,900 ± 490	8.12 ± .18	26,600 ± 580
S	(1.81)	(5,910)	2.25 ± .02	7,380 ± 50	4.03	13,200	6.72 ± .00	22,100 ± 10	7.50 ± .18	24,600 ± 580
7N	(1.78)	(5,840)	(261)	(8,550)	(3.83)	(12,600)	(5.86)	(19,200)	7.74 ± .06	25,400 ± 200
S	1.78	5,840	2.66 ± .07	8,740 ± 240	3.85 ± .46	12,600 ± 1,510	5.70 ± .06	18,700 ± 180	7.45 ± .29	24,400 ± 920
8N	1.78	5,840	2.28	7,490	3.99 ± .14	13,100 ± 430	(5.73)	(18,800)	7.12 ± .09	23,400 ± 280
S	1.81	5,940	2.34 ± .00	7,690 ± 10	4.31 ± .01	14,100 ± 30	(5.97)	(19,600)	7.37 ± .06	24,200 ± 180
9N	1.82	5,960	(2.29)	(7,510)	3.45 ± .03	11,300 ± 110	5.22 ± .04	17,100 ± 120	.....	.....
S	1.86	6,090	2.43 ± .02	7,970 ± 50	3.93 ± .13	12,900 ± 410	6.99 ± .37	22,900 ± 1,200	.....	.....
10N A	1.96 ± .03	6,420 ± 100	2.60 ± .07	8,540 ± 230	(4.21)	(13,800)	4.89 ± .13	16,100 ± 420	.....	.....
S	.....	.....	.....	.....	.....	.....	6.32	20,700	.....	.....
N B	.....	.....	.....	.....	.....	.....	4.22	13,900	.....	.....
S	.....	.....	.....	.....	.....	.....	8.10	26,600	.....	.....
N C	.....	.....	.....	.....	.....	.....	4.76 ± .13	15,600 ± 440	.....	.....
S	.....	.....	.....	.....	.....	.....	6.67	21,900	.....	.....
N D	.....	.....	.....	.....	.....	.....	5.45 ± .11	17,700 ± 370	.....	.....
S	1.96	6,420	(2.60)	(8,540)	4.35 ± .04	14,300 ± 130	(5.44)	(17,800)	.....	.....

Observed Time Intercepts

Profile		Unconsolidated sediment	Semiconsolidated sediment	Consolidated sediment	Basement	Sub-basement
6N		3.15	5.64	7.19	9.16	10.08
S		3.51	5.05	7.83	9.21	9.55
7N		3.08	5.34	7.12	8.86	9.85
S		3.08	5.81	7.18	8.58	9.57
8N		2.26	3.59	6.00	8.18	9.17
S		2.90	4.29	7.30	8.70	9.51
9N		1.45	2.06	3.18	5.80	.....
S		2.16	3.55	5.28	8.70	.....
10N	A	.10	.57	1.13	1.39	.....
S		....	....	....	3.82	.....
N	B	....	....	....	.88	.....
S		....	....	....	5.40	.....
N	C	....	....	....	1.46	.....
S		....	....	....	4.35	.....
N	D	....	....	....	2.24	.....
S		.10	.57	1.60	3.26	.....

* Parentheses indicate assumed values.

TABLE 2.—TRUE VELOCITIES AND THICKNESSES

True Velocities

Profile	Unconsolidated sediment		Semiconsolidated sediment		Consolidated sediment		Basement		Sub-basement	
	km/sec	ft/sec	km/sec	ft/sec	km/sec	ft/sec	km/sec	ft/sec	km/sec	ft/sec
6	(1.79)†	(5,880)	2.66*	8,720*	3.93	12,900	6.70 ± .08	22,000 ± 250	7.76 ± .13	25,500 ± 410
	.....	.....	2.25 ± .02*	7,380 ± 160*	.....	.....	.....	.....	.....	.....
7	1.78	5,840	2.63*	8,600*	3.84*	12,600*	5.78*	19,000*	7.59 ± .15	24,900 ± 470
8	1.79	5,870	2.31	7,580	4.14 ± .07	13,600 ± 220	(5.87)	(19,300)	7.24 ± .05	23,700 ± 170
9	1.84	6,030	2.36*	7,730*	3.68 ± .07	12,100 ± 220	5.97 ± .19	19,600 ± 600	.....	.....
10	1.96	6,420	2.60*	8,540*	4.28*	14,000*	5.45	17,900	.....	.....

Thicknesses

Profile	Water			Unconsolidated sediment		Semiconsolidated sediment		Consolidated sediment		Basement	
	km	ft	fms	km	ft	km	ft	km	ft	km	ft
6N	4.40	14,400	2,400	1.02	3,350	1.43	4,690	3.38	11,100	5.11	16,800
S	4.90	16,100	2,670	.33	1,100	2.05	6,740	1.95	6,390	1.37	4,490
7N	4.36	14,300	2,380	.69	2,300	1.98	6,500	3.03	9,900	2.89	9,200
S	4.36	14,300	2,380	1.27	4,200	1.03	3,400	2.31	7,600	3.26	10,400
8N	3.01	9,900	1,650	.71	2,300	2.12	6,900	5.38	17,600	1.90	9,160
S	3.76	12,300	2,060	.62	2,000	2.75	9,000	2.84	9,300	1.90	9,160
9N	1.82	6,000	990	.22	720	1.06	3,500	5.50	18,000	....	.....
S	2.70	8,900	1,480	1.04	3,400	1.42	4,700	6.88	22,600	....	.....
10N	.07	240	40	.76	2,500	.57	1,900	.70	2,300	....	.....
S	1.75	5,700	960	.76	2,500	1.34	4,400	5.37	17,600	....	.....

* Unreversed.

† Parentheses indicate assumed values.

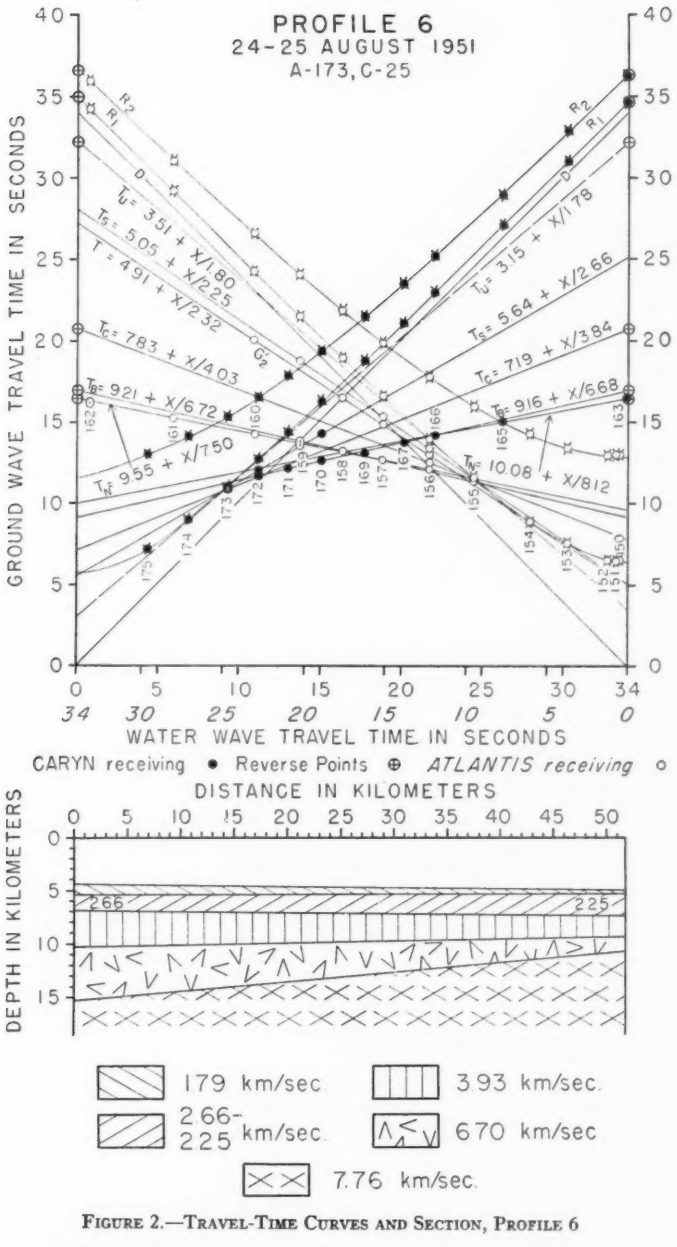


FIGURE 2.—TRAVEL-TIME CURVES AND SECTION, PROFILE 6

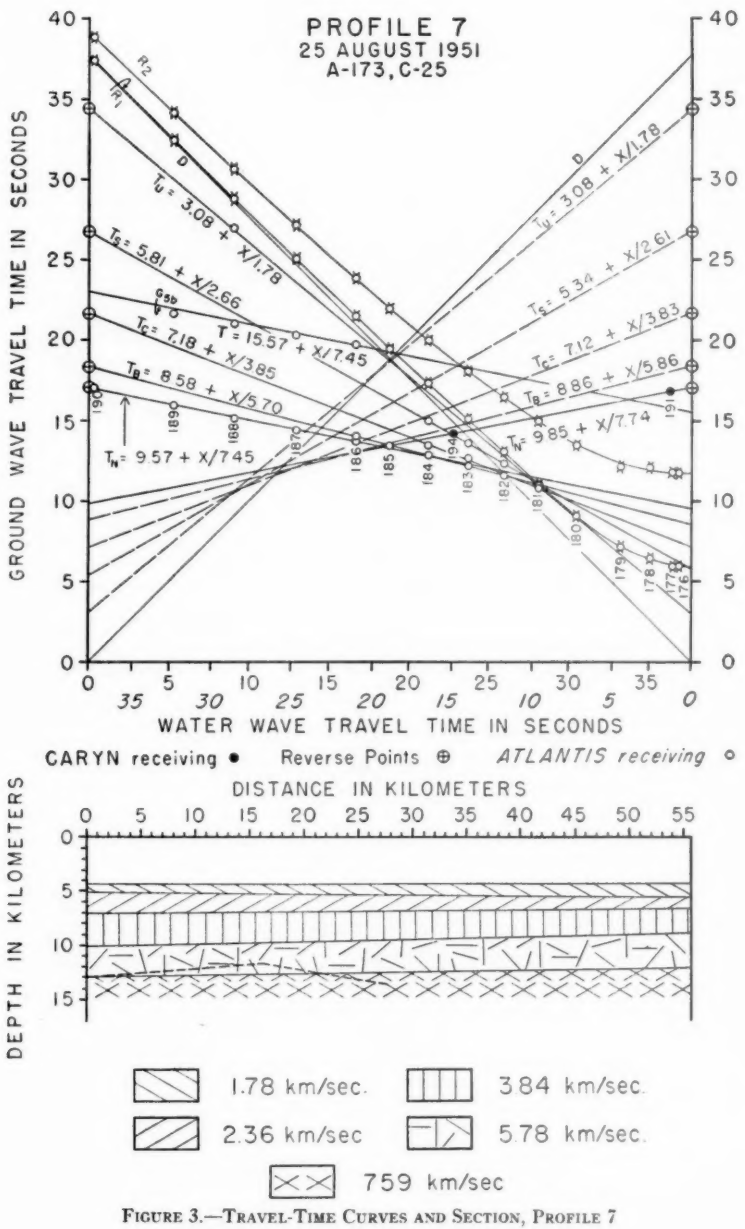

PROFILE 7
25 AUGUST 1951
A-173, C-25
GROUND WAVE TRAVEL TIME IN SECONDS
WATER WAVE TRAVEL TIME IN SECONDS
T_U = 3.08 + X/1.78
T_S = 5.81 + X/2.66
T_C = 7.18 + X/3.85
T_B = 8.58 + X/5.70
T_N = 9.57 + X/7.45
T = 15.57 + X/7.45
T_U = 3.08 + X/1.78
T_S = 5.34 + X/2.61
T_C = 7.12 + X/3.83
T_B = 8.86 + X/5.86
T_N = 9.85 + X/7.74
CARYN receiving ● Reverse Points ⊕ ATLANTIS receiving ○
DISTANCE IN KILOMETERS
DEPTH IN KILOMETERS
1.78 km/sec.
2.36 km/sec
3.84 km/sec.
5.78 km/sec.
759 km/sec

FIGURE 3.—TRAVEL-TIME CURVES AND SECTION, PROFILE 7

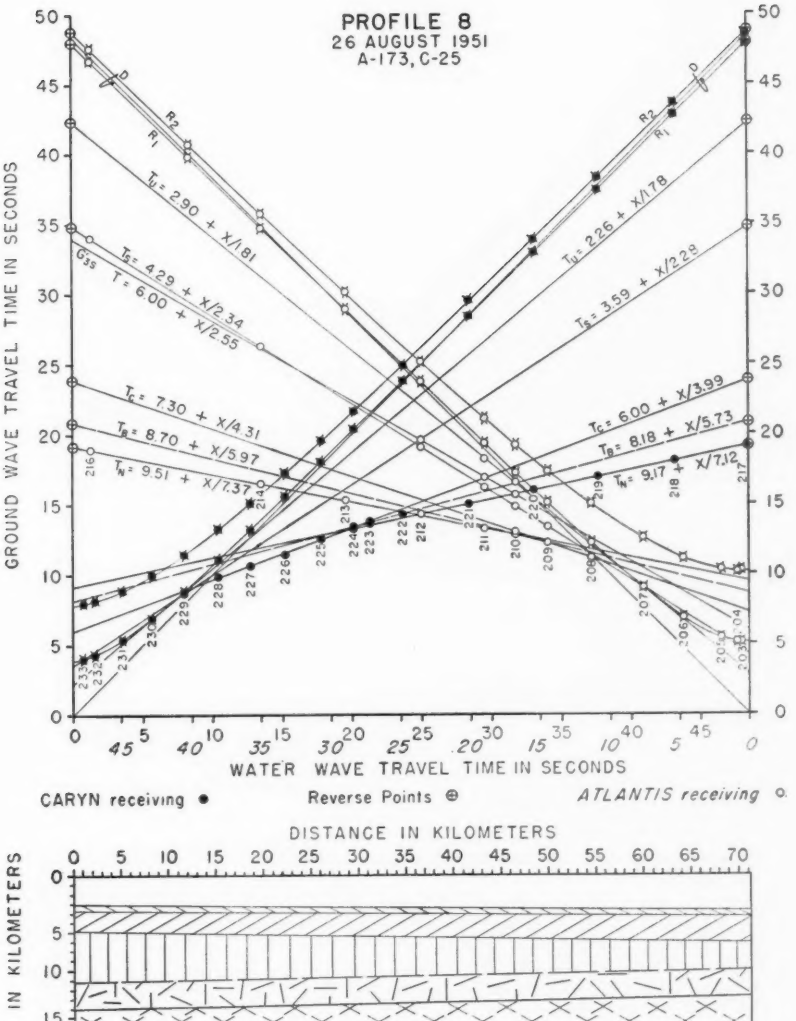


FIGURE 4.—TRAVEL-TIME CURVES AND SECTION, PROFILE 8

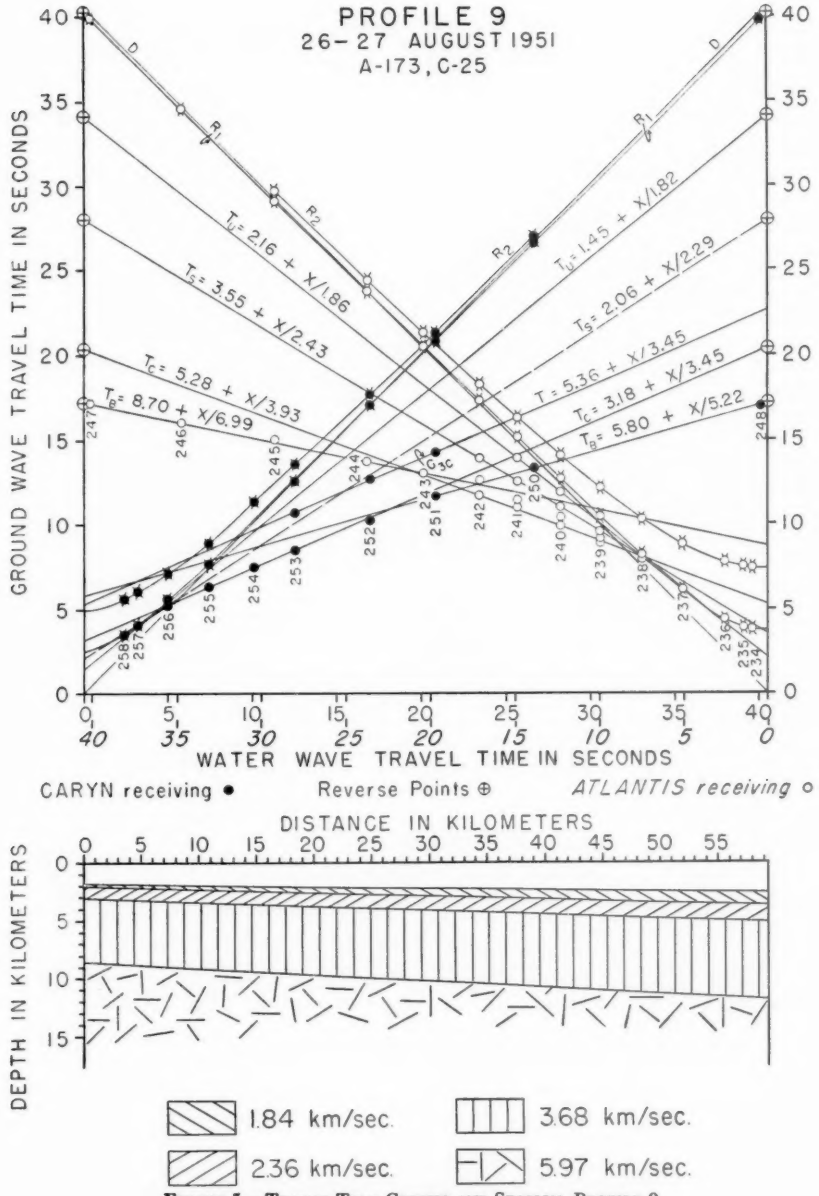


FIGURE 5.—TRAVEL-TIME CURVES AND SECTION, PROFILE 9

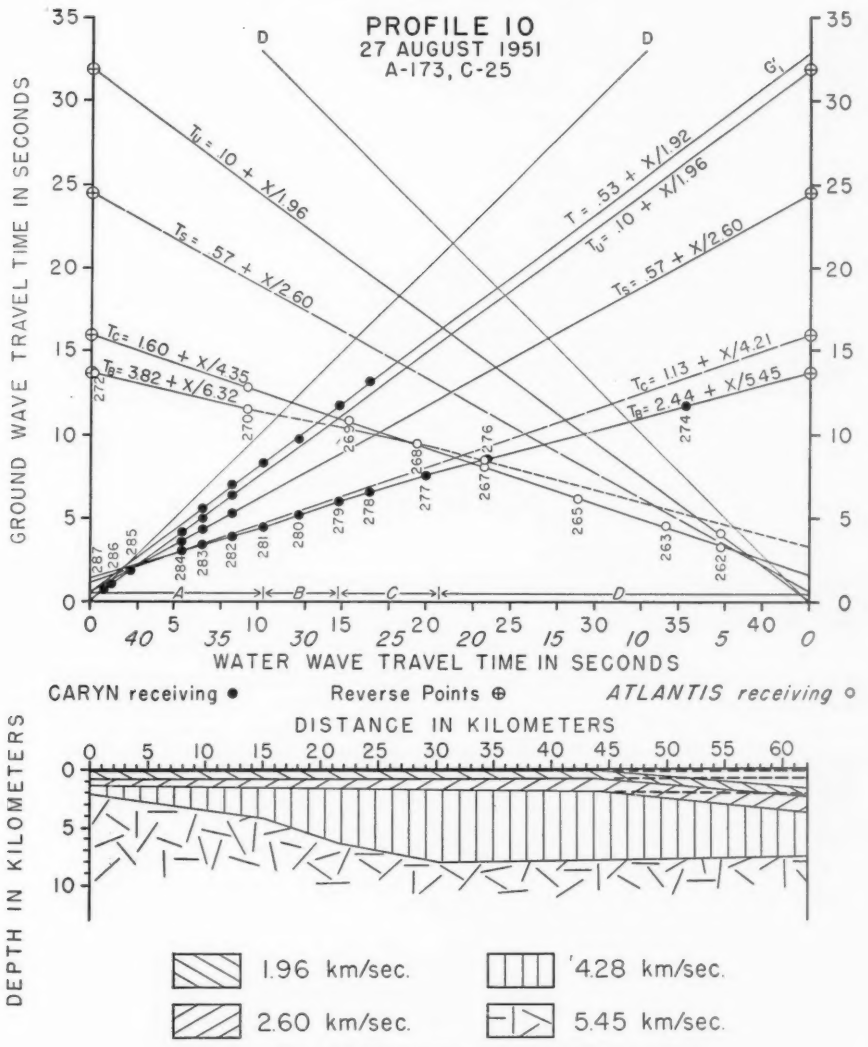


FIGURE 6.—TRAVEL-TIME CURVES AND SECTION, PROFILE 10

arrivals. The latter line is unreversed; the reverse was chosen to minimize the discrepancy in sediment thickness between the north end of this profile and the south end of profile 10. The consolidated sediment lines were drawn assuming only one layer; however there is a good indication on both sides of the profile of an increasing velocity with depth. The assumption of one layer was made to preserve the continuity of structure with the other profiles. A rather poor line of four second arrivals on the ATLANTIS receiving end suggests still another layer, but was not considered sufficient evidence to be included in the section.

Three second arrivals for CARYN receiving form a line parallel to the consolidated-sediment line at a distance of 2.2 seconds above it (G_{3c}; *See* Pl. 1, shot 253). These are believed to have been reflected once within the combined layer of unconsolidated and semicon-

solidated sediment (Fig. 7b). The time delay expected by such a reflection cannot be computed exactly since it will vary according to the reverse line chosen for the semiconsolidated layer, and according to the place where the reflection occurs, owing to the relative slope of the layer interfaces. However, reasonable assumptions result in values for the delay bracketing those actually found.

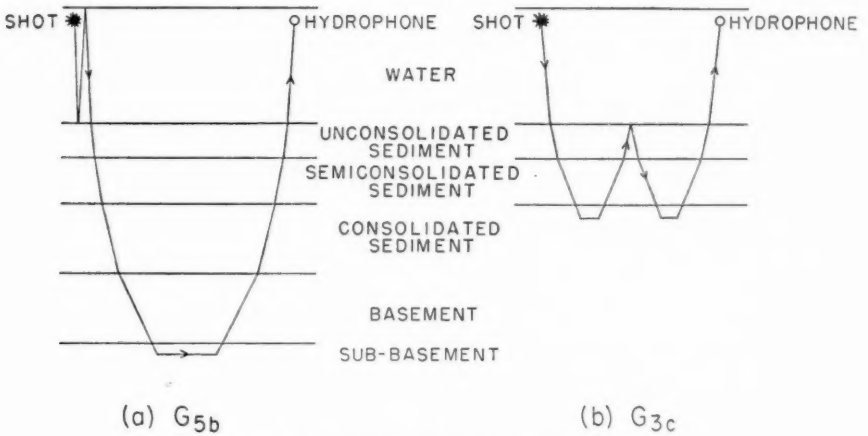


FIGURE 7.—RAY DIAGRAMS OF REFLECTED REFRACTED RAYS

Profile 10 (Fig. 6)

This profile was shot partly on the continental shelf and partly on the continental slope. Arrivals on all shots were corrected to a water depth of 40 fathoms before plotting the travel-time curve (dashed lines in the section in Fig. 6); the slope was restored to the section after the velocity and depth computations had been made (solid lines).

The unconsolidated sediment layer on the CARYN receiving end is determined by three first arrivals which line up well with three second arrivals. This gives weight to other lines determined by second arrivals alone. The semiconsolidated line is again unreversed, the reversed being chosen to minimze the thickness discrepancy with profile 9. The consolidated sediment was completely masked at the CARYN end, hence a line was chosen with minimum intercept corresponding to maximum possible thickness of the consolidated sediment layer.

The basement line was drawn with three changes in slope indicating changes in dip of the basement surface. The segment between 10 and 15 seconds, B, for CARYN receiving has been drawn with minimum slope change, corresponding to minimum dip of the basement surface. The break downward at 20.7 seconds for CARYN receiving is believed to correspond to a change in basement dip rather than to another layer since there is no indication of more than one layer in the ATLANTIS receiving direction.

A good set of second arrivals for CARYN receiving form a line above and nearly parallel to the unconsolidated sediment line (G′, *see* Pl. 1, shot 282). It has an apparent velocity of 1.92±.03 km/sec compared with 1.96± .03 km/sec for the unconsolidated line. This velocity cannot be that of shear waves in any of the layers, since the ratio of compressional velocity to this velocity would be 1.35 for the semiconsolidated layer, or 2.19 for the consolidated layer, values which vary too much from those normally expected. It is possible, within the limit of error, that the velocity of this line is slightly greater than that of the unconsolidated line. The arrivals might then be explained as being refracted from beneath a low velocity layer of 0.1–0.2 km thickness within the unconsolidated sediment. The existence of such a layer would increase the calculated depths to the other layers by one or two tenths of a kilometer. The authors have

been unable to find any other explanation for these rather good arrivals.

Discussion

The section (Fig. 8) includes profile 16 from Press and Beckmann (1953, p. 308) which is in line with this section about half way between profile 10 and the shore.

The discrepancy between the north end of profile 9 and the south end of profile 10 is believed to be due to the lateral displacement between the two receiving points, and to the lack of precision in the topographic corrections which are particularly large on profile 10.

The unconsolidated sediment has an average velocity of 1.83 km/sec and a maximum deviation of 7 per cent from that average. Its highest velocity is found near the edge of the continental shelf, decreasing gradually seaward and more rapidly toward land. It is quite constant in thickness (about .5 km) throughout most of the section, thinning at the north end.

The semiconsolidated sediment has an average velocity of 2.47 km/sec with a maximum deviation of 9 per cent. Its variations in velocity are irregular. It has a maximum thickness of 2.7 km 150 km from the shelf edge, and pinches out on the shelf; this layer was not found by Press and Beckmann on any of their profiles.

The velocity in the consolidated sediment has an average value of 3.97 km/sec with a maximum deviation of 8 per cent. The velocity variations are irregular with a slight indication of increasing velocity toward shore. The high velocity (4.34 km/sec) on profile 16 is not representative of the banks, since Press and Beckmann found a range of 3.38–4.34 km/sec, profile 16 containing the highest velocity. The layer has a maximum thickness of 6.8 km at the south end of profile 9, thinning to an average of about 3 km to the south; northward it attains a secondary maximum of over 6 km under the shelf edge, then thins rapidly to only .70 km as the basement rises sharply.

With the exception of profile 6, the average basement velocity is 5.73 km/sec with a maximum deviation of 5 per cent. The larger velocities are to the south, quite possibly because of the effect of greater depth. Maximum thickness is under the southern part of the shelf where the layer below is not reached. The nature of the transition from 5.78 to 6.70 km/sec between profiles 7 and 6 is not known because of the 70-km gap. The thickness of the basement between this transition and profile 9 is not certain since this layer on profile 7 is unreversed and the thickness plotted for profile 8 is merely a maximum value.

The average sub-basement velocity on profiles 6, 7, and 8 is 7.53 km/sec with a maximum deviation of 4 per cent. The velocities decrease regularly northward.

The writers' interpretation of the section is shown in Figure 8b. The sub-basement layers of the three southernmost profiles have been correlated on the basis of their velocity similarity and their corresponding positions in their respective columns. The sub-basement surface dips steeply to the north of profile 8, reaching a minimum depth of 18 km beneath the center of profile 9.

Geological Implications

The basement velocities of the present section are typical of the basement complex all along the North American Atlantic coast, from North Carolina to Nova Scotia (Geophysical Investigations, Parts I–IX; Skeels, 1950), and of granites and metamorphics in general (Birch *et al.*, 1942, p. 95; Gutenberg, 1951, p. 233). The basement can thus be definitely correlated with the Precambrian granites and metasediments of southeast Newfoundland.

There is, however, no known sedimentary column later than Paleozoic anywhere in Newfoundland with which to compare the present results. The nearest section is that described by Officer and Ewing (1954) across the continental shelf, slope, and rise southeast of Halifax. That section is generally similar to the present one except that the consolidated sediment is limited to a lens beneath the shelf, the unconsolidated and semiconsolidated layers alone constituting the great sediment thickness below the continental slope. Average velocities for these layers are 1.72 km/sec and 2.69 km/sec, respectively, as compared with 1.83 km/sec and 2.49 km/sec found for these layers in the present work. On the basis of comparison with other parts of the coastal plain and with samples taken from submarine

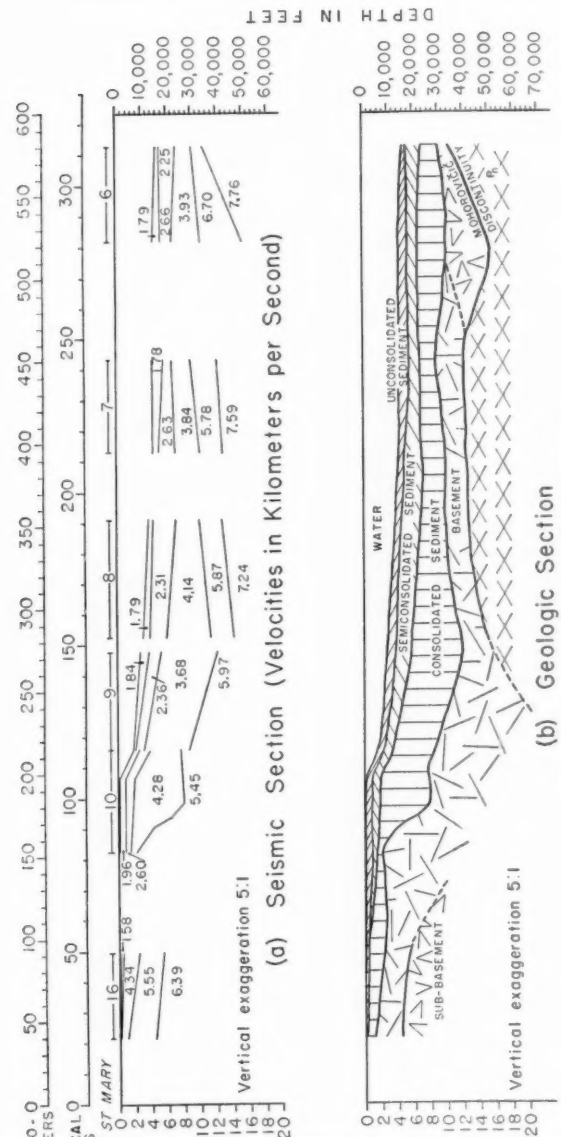


FIGURE 8.—SEISMIC AND GEOLOGIC SECTIONS

canyons, the unconsolidated sediment is identified by them as Upper Cretaceous, Tertiary, and Quaternary; the semiconsolidated as Cretaceous, primarily Lower Cretaceous, and possibly Jurassic. The similarity in velocities and general structure between the two sections suggests the same identification in the present case, but owing to the lack of any direct evidence this cannot be verified. The lack of semiconsolidated sediment on the Banks suggests a considerable period of time during which the present shelf area was emerged.

A striking feature of the Grand Banks section is the presence of the thick consolidated sediment layer. Its velocity is similar to that (3.87 km/sec) of the Triassic sediment found in the Gulf of Maine by Drake *et al.* (1954), and also to the value, 4.11 km/sec, quoted by Birch *et al.* (1942, p. 97) for both Cretaceous limestone and Devonian shale and sandstone. These representative values indicate a wide range for the possible age of the sediment; furthermore, in the latter cases, the measurements were made under conditions quite different from those of the present work. Clearly any identification of layers with so little evidence is in the realm of speculation. However, we might guess that the layer includes the Triassic, perhaps some of the Jurassic, and may extend well back into the Paleozoic. Possibly the Acadian disturbance marked the beginning of the deposition of this layer as it seems to have marked the end of deposition in southeast Newfoundland. (*See* Eardley, 1951, Fig. 109, p. 188.)

The distinct decrease in the sub-basement velocity as the shore is approached is noteworthy since it may indicate that the "ultrabasic" material beneath the discontinuity undergoes considerable lithologic change. Whether this change is typical of the transition from oceanic to continental structure cannot be determined until sections from other localities are available. In the present case, however, the picture is one of a fairly complicated and gradual transition rather than the simple one of a continental block "floating" on the mantle material in equilibrium with the thin oceanic crust.

References Cited

Birch, A. F., Schairer, J. R., and Spicer, H. C. (editors), 1942, Handbook of physical constants: Geol. Soc. America Spec. Paper No. 36, 325 p.

Drake, C. L., Worzel, J. L., and Beckmann, W. C., 1954, Geophysical investigations in the emerged and submerged Atlantic coastal plain, Part IX: Gulf of Maine: Geol. Soc. America Bull., v. 65, p. 957–970.

Eardley, A. J., 1951, Structural geology of North America: N. Y., Harper & Bros., 624 p.

Ewing, M., Crary, A. P., and Rutherford, H. M., 1937, Geophysical investigations in the emerged and submerged Atlantic coastal plain, Part I: Geol. Soc. America Bull., v. 48, p. 753–802.

Ewing, M., Sutton, G. H., and Officer, C. B., 1954, Seismic refraction measurements in the Atlantic Ocean, Part VI: typical deep stations; North America basin: Seismol. Soc. America Bull., v. 44, p. 21–38.

Ewing, M., Woollard, G. P., and Vine, A. C., 1939, Geophysical investigations in the emerged and submerged Atlantic coastal plain, Part III: Barnegat Bay, New Jersey, section: Geol. Soc. America Bull., v. 50, p. 257–296.

—— 1940, Geophysical investigations in the emerged and submerged Atlantic coastal plain, Part IV: Cape May, New Jersey, section: Geol. Soc. America Bull., v. 51, p. 1821–1840.

Ewing, M., Worzel, J. L., Steenland, N. C., and Press, F., 1950, Geophysical investigations in the emerged and submerged Atlantic coastal plain, Part V: Woods Hole, New York, and Cape May sections: Geol. Soc. America Bull., v. 61, p. 877–892.

Gutenberg, B. (editor), 1951, Internal Constitution of the Earth: N. Y., Dover Publications, 2d ed., 439 p..

Hoel, P. G., 1947, Introduction to Mathematical Statistics: N. Y., Wiley and Sons, 258 p.

Miller, B. L., 1937, Geophysical investigations in the emerged and submerged Atlantic coastal plain, Part II: Geological significance of the geophysical data: Geol. Soc. America Bull., vol. 48, p. 803–812.

Officer, C. B., and Ewing, M., 1954, Geophysical investigations in the emerged and submerged Atlantic coastal plain, Part VII: Continental shelf, continental slope, and continental rise south of Nova Scotia: Geol. Soc. America Bull., v. 65, p. 653–670.

Officer, C. B., and Wuenschel, P. C., 1951, Reduction of deep sea refraction data: Tech. Rep. No. 1, Contract NObsr 43355, Lamont Geol. Observatory.

Officer, C. B., Ewing, M., and Wuenschel, P. C., 1952, Seismic refraction measurements in the Atlantic Ocean: Part IV: Bermuda, Bermuda Rise, and Nares Basin: Geol. Soc. America Bull., v. 63, p. 777–808.

Oliver, J. E., and Drake, C. L., 1951, Geophysical investigations in the emerged and submerged Atlantic coastal plain, Part VI: The Long Island area: Geol. Soc. America Bull., v. 62, p. 1287–1296.

Press, F., and Beckmann, W. C., 1954, Geophysical

DETROIT PUBLIC LIBRARY

investigations in the emerged and submerged Atlantic coastal plain, Part VIII: Grand Banks and adjacent shelves: Geol. Soc. America Bull., v. 65, p. 299–314.

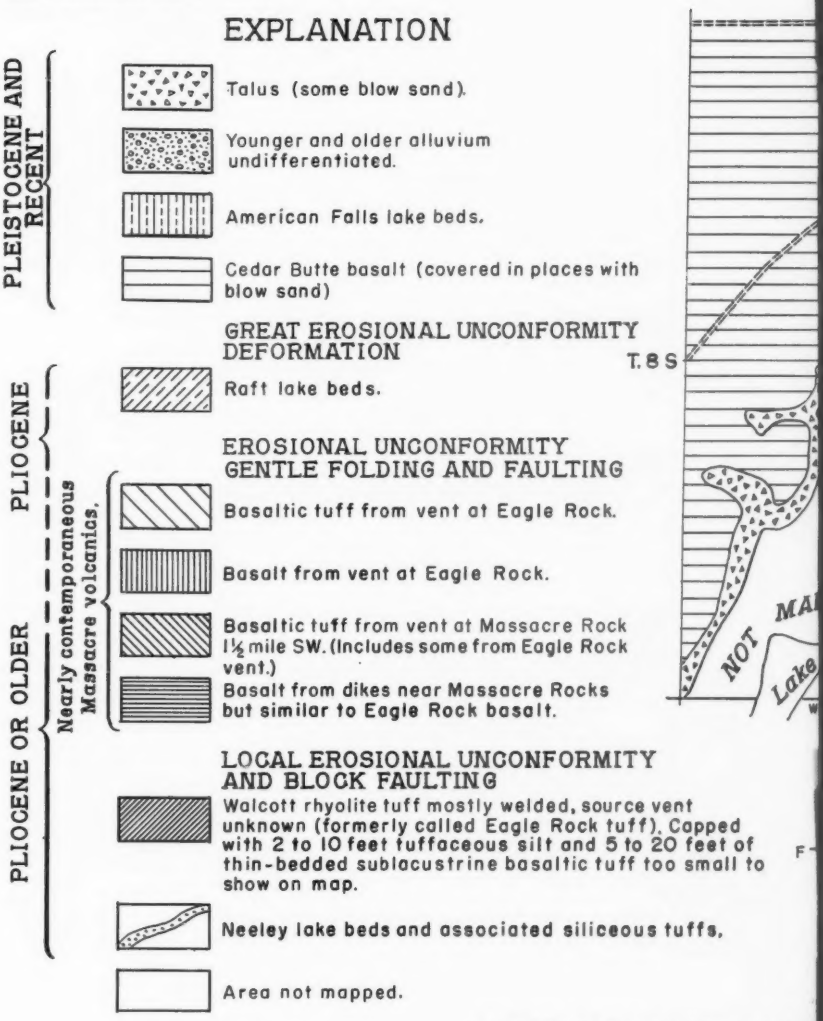
Skeels, D. C., 1950, Geophysical data on the North Carolina coastal plain: Geophysics, v. 15, p. 409–426.

Sutton, G. H., 1952, Three Channel amplifier for use in refraction and sound measurements at sea: Tech. Rept. no. 2, Contract NObsr 43355, Lamont Geol. Observatory.

LAMONT GEOLOGICAL OBSERVATORY, COLUMBIA UNIVERSITY, PALISADES, N. Y.

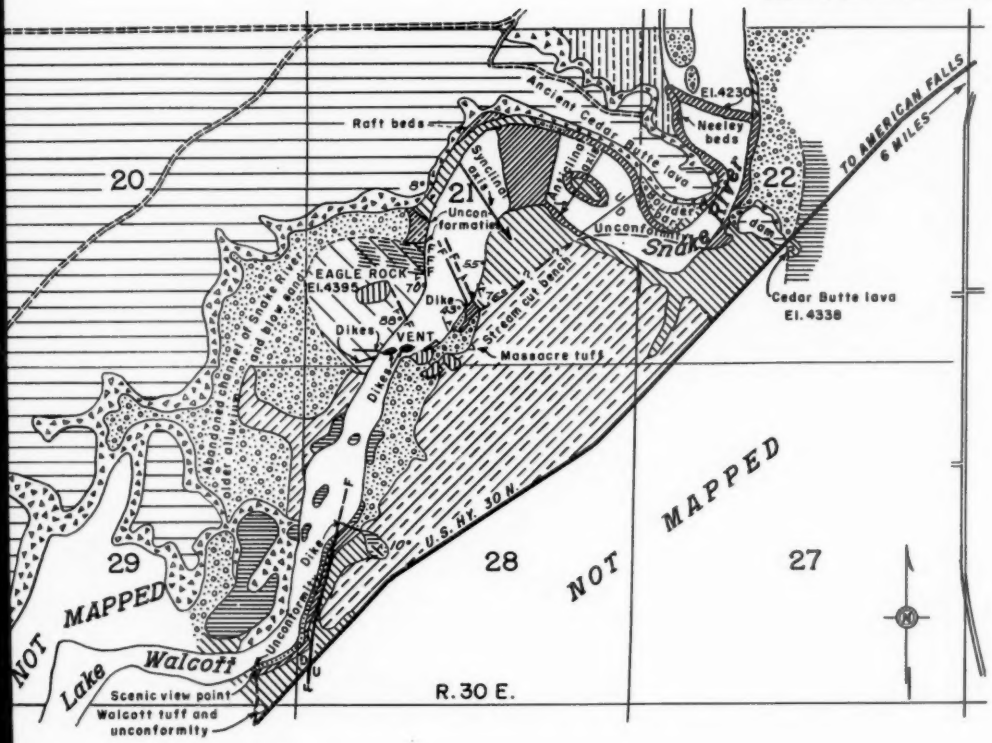
MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, OCTOBER 13, 1954

LAMONT GEOLOGICAL OBSERVATORY CONTRIBUTION NO. 169


EXPLANATION
PLEISTOCENE AND RECENT
Talus (some blow sand).
Younger and older alluvium undifferentiated.
American Falls lake beds.
Cedar Butte basalt (covered in places with blow sand)
GREAT EROSIONAL UNCONFORMITY
DEFORMATION
PLIOCENE
Raft lake beds.
EROSIONAL UNCONFORMITY
GENTLE FOLDING AND FAULTING
PLIOCENE OR OLDER
Nearly contemporaneous Massacre volcanics.
Basaltic tuff from vent at Eagle Rock.
Basalt from vent at Eagle Rock.
Basaltic tuff from vent at Massacre Rock 1½ mile SW. (Includes some from Eagle Rock vent.)
Basalt from dikes near Massacre Rocks but similar to Eagle Rock basalt.
LOCAL EROSIONAL UNCONFORMITY
AND BLOCK FAULTING
Walcott rhyolite tuff mostly welded, source vent unknown (formerly called Eagle Rock tuff). Capped with 2 to 10 feet tuffaceous silt and 5 to 20 feet of thin-bedded sublacustrine basaltic tuff too small to show on map.
Neeley lake beds and associated siliceous tuffs.
Area not mapped.
T. 8 S
NOT MA
Lake

GEOLOGIC MAP OF E

Stearns and Isotoff, Pl. 1



Basaltic dike.

Fault, dashed where concealed.

Strike and dip.

By H. T. Stearns

HOPE, IDAHO NOVEMBER 1952

0 1 Mile

OF EAGLE ROCK AREA, IDAHO

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 67, PP. 19-34, 5 FIGS., 5 PLS. JANUARY 1956

STRATIGRAPHIC SEQUENCE IN THE EAGLE ROCK VOLCANIC AREA NEAR AMERICAN FALLS, IDAHO

BY HAROLD T. STEARNS AND ANDREI ISOTOFF

ABSTRACT

Excellent exposures in Snake River canyon in the Eagle Rock area near American Falls, Idaho, were supplemented by numerous drill holes in connection with the exploration for a damsite. The rocks are Lower Pliocene (?) Neeley lake beds and associated basaltic and siliceous sediments and tuffs possibly correlative with the Salt Lake formation to the east and the Payette formation to the west. Above the Neeley formation a welded rhyolite tuff (ignimbrite) contains lithophysae and spherulites and shows four distinct phases. Next higher is a siliceous tuffaceous shallow-water sediment, a thin-bedded sublacustrine basaltic tuff, with very thin diatomaceous interbeds, and finally thick basaltic tuffs, breccias, dikes, and lava flows of the Massacre volcanics. Agglutinated basaltic tuffs are also present. Unconformable on these rocks are the Raft lake beds, possibly correlative with the Lake Idaho deposits farther west, of late Pliocene age. A major erosional unconformity separates the Tertiary rocks from the late Pleistocene Cedar Butte basalt which displaced Snake River for 55 miles and produced a lake 40 miles long and 12 miles wide. The beds deposited by this lake constitute the American Falls formation. Abandoned spring coves cut in the downstream end of the Cedar Butte basalt testify to heavy leakage from this ancient lake. The region was warped into gentle anticlines and synclines near the close of the Tertiary and faulted into small blocks. Several erosional unconformities were found. The petrography is described.

CONTENTS

TEXT

	Page
Introduction	20
Acknowledgments	20
Location	20
Geomorphology	20
Stratigraphy	20
General	20
Lower Pliocene (?) rocks	20
Neeley lake beds and associated tuffs	20
Walcott welded tuff	23
Formation A	23
Formation B	24
Massacre volcanics (Formation C)	24
Upper Pliocene (?) rocks	27
Formation D	27
Raft Lake beds (Formation E)	27
Pleistocene rocks	27
Cedar Butte basalt	27
American Falls lake beds	28
Late Pleistocene and Recent deposits	28
Structure	28
Geologic history	29
Tertiary time	29
Pleistocene time	32
Pleistocene and Recent time	32
Petrography	32
References cited	34

ILLUSTRATIONS

Figure	Page
1. Topographic map of Eagle Rock area near American Falls, Idaho	21
2. Logs of diamond-drill holes 9 and 16 near Eagle Rock, Idaho	22
3. Geologic sketch of the right bank of Snake River near Eagle Rock	26
4. Sketch showing either an unconformity or a fault terminating Neeley lake beds, Walcott tuff, and Formations A and B	29
5. Composite stratigraphic section of Eagle Rock area, Idaho	31

Plate	Facing page
1. Geologic map of Eagle Rock area, Idaho	19
	Following page
2. Walcott welded tuff near American Falls Dam, Idaho	24
3. Rocks exposed in Snake River Canyon, Idaho	24
4. Typical exposures of Formations A, B, D, E, and Walcott tuff near Eagle Rock, Idaho	24
5. Faulting in Walcott tuff near Eagle Rock, Idaho	24

TABLES

Table	Page
1. Comparison of two outcrops of Walcott formation	23
2. Accidental ejecta from Formation C	33

Introduction

Stearns mapped the geology of the area in 1952–1953 for the Idaho Power Company in connection with an extensive diamond-drilling program in search of a damsite. He had previously mapped the area in reconnaissance for the U. S. Geological Survey (Stearns *et al.*, 1938, Pl. 6). Isotoff subsequently studied the rocks and cores in thin section, made further field investigations which helped to clarify the stratigraphy, and prepared the petrographic section.

Acknowledgments

The senior writer is indebted to the Idaho Power Company for co-operation in releasing the scientific data and geologic illustrations used in this report. Messrs. Russell Biaggne, Roy Treat, James Nitta, and Stanley Stearns prepared the illustrations.

Location

The volcanic area is named from Eagle Rock, a prominent lava-capped hill on the northwest bank of Snake River, 7½ miles downstream from American Falls, in Power County in southeastern Idaho (Pl. 3, fig. 2). The area mapped is about 4 square miles in T. 8 S., R. 30 E., in the Rockland Valley quadrangle. The topography of the area is shown in Figure 1. It is readily accessible from U. S. Highway 30 N. which lies along the south side of the river.

Geomorphology

The exposure of the complicated sequence of Cenozoic volcanic and sedimentary rocks resulted from the pushing southward of Snake River into the mouth of the broad Rockland Valley by a voluminous late Pleistocene basalt flow from Cedar Butte. Snake River was impounded to form the ancient American Falls lake which extended about 40 miles upstream from the lava dam shown in Figure 1 of Plate 3. When Snake River overtopped the dam in section 22 (Pl. 1) it followed the southern margin of the basalt and flowed over the older Tertiary rocks. The river has since cut a canyon 200 feet deep into a series of late Tertiary volcanic and sedimentary rocks which give a clue to the basement of the extensive Snake River lava plain (Pl. 3, fig. 2).

Stratigraphy

General

The areal distribution of the formations is shown in Plate 1, and the stratigraphic sequence in Figure 5. Lack of determinative fossils makes the age of all Tertiary rocks uncertain. Similar gently warped and faulted siliceous volcanic rocks have been mapped in southeastern Idaho as the Salt Lake formation of Pliocene (?) age (Mansfield, 1927, p. 203; Mansfield and Ross, 1935). Kirkham (1931a, p. 579) called them the "Tertiary late lavas". They were described as Lower Pliocene (?) rocks by Stearns *et al.* (1938, p. 43) because they are older than the Hagerman lake beds of late Pliocene age which lie downstream from them and in which determinative fossils have been found (p. 53). Anderson (1931, p. 37–44) describes a somewhat similar series about 2500 feet thick in near-by Cassia County in which the lower 1700 feet is chiefly sediments and ash beds and the upper 800 feet is chiefly rhyolites and ash. He correlated the rocks with the Salt Lake formation of the Fort Hall area and the Payette formation in southwestern Idaho and assigned them to the upper Miocene or lower Pliocene. The Tertiary rocks in the Eagle Rock area are correlated tentatively with those in Cassia County and the Fort Hall area and assigned to the lower Pliocene (?), although they may be upper Miocene.

Lower Pliocene (?) Rocks

Neeley lake beds and associated tuffs.—The Neeley lake beds comprise very diverse rocks laid down in a shallow lake. They were first described and named by Stearns *et al.* (1938, p. 43). The dominant beds are pink siliceous tuffs and tuffaceous sandstones which give the formation a light color (Fig. 2; Pl. 1; Pl. 3, fig. 2). Secondary calcite is abundant. Beds of marly limestone a few inches to a few feet thick and thin clay and silty clay layers are interbedded with the tuffs indicating lacustrine

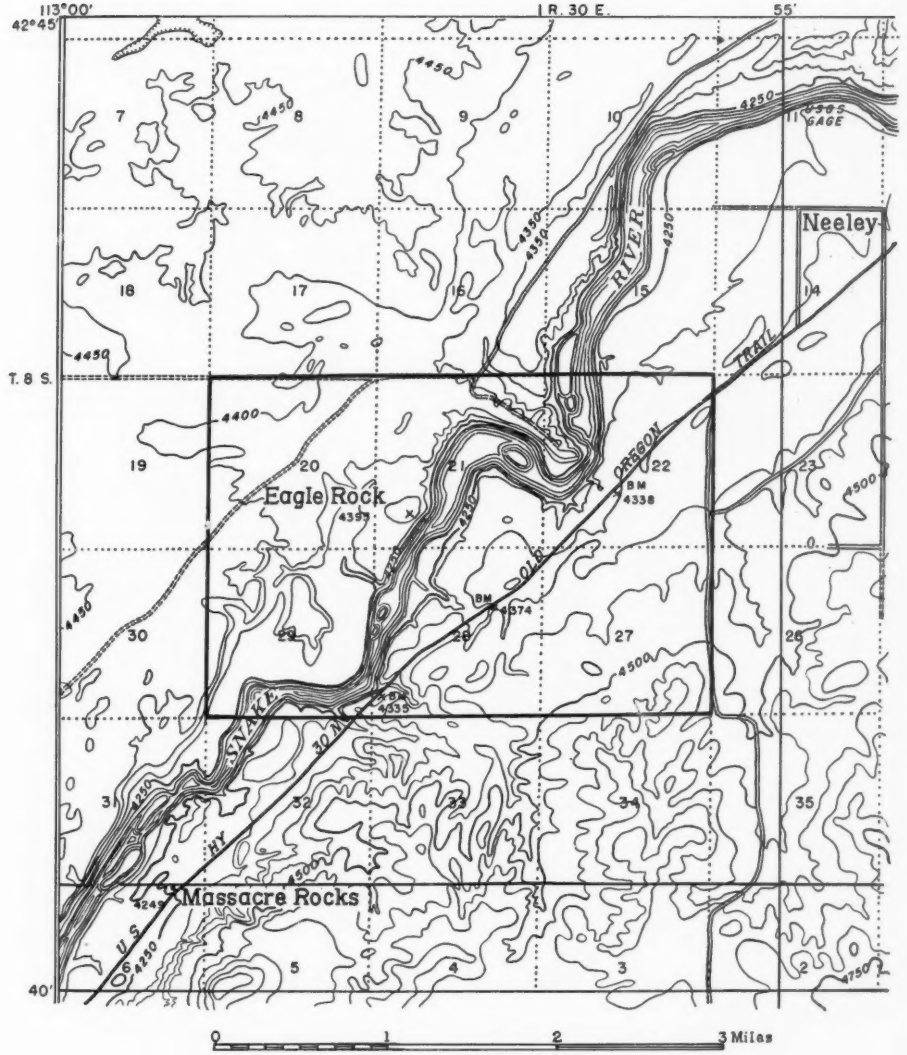


FIGURE 1.—TOPOGRAPHIC MAP OF EAGLE ROCK AREA NEAR AMERICAN FALLS, IDAHO

conditions. Conglomerate beds a few inches to a few feet thick containing water-worn basalt, rhyolite, and quartzite pebbles indicate deltaic deposits. Some beds are hard, but others are friable. Absence of interbedded soils or dune deposits suggests there were no prolonged dry intervals. Holes 9 and 16 (Fig. 2) penetrated this formation, but drilling did not reach the bottom of the formation. The stratigraphic position of the formation is somewhat similar to the Payette lake beds of Middle or Late Miocene age in southwestern Idaho (Kirkham, 1931b, p. 232). The Payette beds contain both basaltic and siliceous tuffaceous sediments but

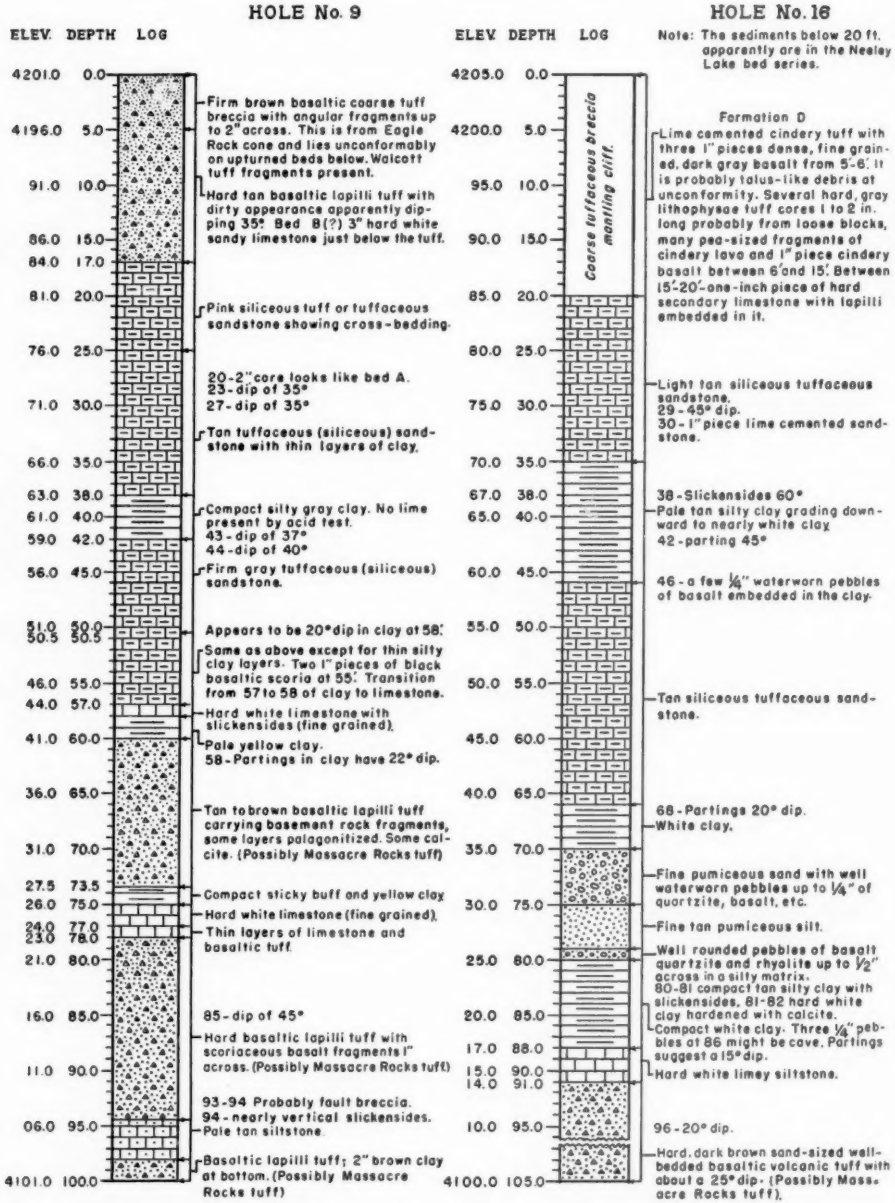

HOLE No. 9
ELEV. DEPTH LOG
4201.0 0.0
4196.0 5.0
91.0 10.0
86.0 15.0
84.0 17.0
81.0 20.0
76.0 25.0
71.0 30.0
66.0 35.0
63.0 38.0
61.0 40.0
59.0 42.0
56.0 45.0
51.0 50.0
50.5 50.5
46.0 55.0
44.0 57.0
41.0 60.0
36.0 65.0
31.0 70.0
27.5 73.5
26.0 75.0
24.0 77.0
23.0 78.0
21.0 80.0
16.0 85.0
11.0 90.0
06.0 95.0
4101.0 100.0
Firm brown basaltic coarse tuff breccia with angular fragments up to 2" across. This is from Eagle Rock cone and lies unconformably on upturned beds below. Walcott tuff fragments present.
Hard tan basaltic lapilli tuff with dirty appearance apparently dipping 35°. Bed 8(?) 3" hard white sandy limestone just below the tuff.
Pink siliceous tuff or tuffaceous sandstone showing cross-bedding.
20-2" core looks like bed A.
23-dip of 35°
27-dip of 35°
Tan tuffaceous (siliceous) sandstone with thin layers of clay.
Compact silty gray clay. No lime present by acid test.
43-dip of 37°
44-dip of 40°
Firm gray tuffaceous (siliceous) sandstone.
Appears to be 20° dip in clay at 58'.
Some as above except for thin silty clay layers. Two 1" pieces of black basaltic scoria at 55'. Transition from 57 to 58 of clay to limestone.
Hard white limestone with slickensides (fine grained).
Pale yellow clay.
58-Partings in clay have 22° dip.
Tan to brown basaltic lapilli tuff carrying basement rock fragments, some layers palagonitized. Some calcite. (Possibly Massacre Rocks tuff)
Compact sticky buff and yellow clay
Hard white limestone (fine grained).
Thin layers of limestone and basaltic tuff.
85-dip of 45°
Hard basaltic lapilli tuff with scoriaceous basalt fragments 1" across. (Possibly Massacre Rocks tuff)
93-94 Probably fault breccia.
94-nearly vertical slickensides.
Pale tan siltstone.
Basaltic lapilli tuff; 2" brown clay at bottom. (Possibly Massacre Rocks tuff)
HOLE No. 16
ELEV. DEPTH LOG
4205.0 0.0
4200.0 5.0
95.0 10.0
90.0 15.0
85.0 20.0
80.0 25.0
75.0 30.0
70.0 35.0
67.0 38.0
65.0 40.0
60.0 45.0
55.0 50.0
50.0 55.0
45.0 60.0
40.0 65.0
35.0 70.0
30.0 75.0
25.0 80.0
20.0 85.0
17.0 88.0
15.0 90.0
14.0 91.0
10.0 95.0
4100.0 105.0
Coarse tuffaceous breccia mantling cliff.
Note: The sediments below 20 ft. apparently are in the Neeley Lake bed series.
Formation D
Lime cemented cindery tuff with three 1" pieces dense, fine grained, dark gray basalt from 5'-6'. It is probably talus-like debris at unconformity. Several hard, gray lithophysae tuff cores 1 to 2 in. long probably from loose blocks, many pea-sized fragments of cindery lava and 1" piece cindery basalt between 6' and 15'. Between 15'-20'-one-inch piece of hard secondary limestone with lapilli embedded in it.
Light tan siliceous tuffaceous sandstone.
29-45° dip.
30-1" piece lime cemented sandstone.
38-Slickensides 60°
Pale tan silty clay grading downward to nearly white clay.
42-parting 45°
46-a few ¼" waterworn pebbles of basalt embedded in the clay.
Tan siliceous tuffaceous sandstone.
68-Partings 20° dip.
White clay.
Fine pumiceous sand with well waterworn pebbles up to ¼" of quartzite, basalt, etc.
Fine tan pumiceous silt.
Well rounded pebbles of basalt quartzite and rhyolite up to ½" across in a silty matrix.
80-81 compact tan silty clay with slickensides. 81-82 hard white clay hardened with calcite.
Compact white clay. Three ¼" pebbles at 86 might be cave. Partings suggest a 15° dip.
Hard white limey siltstone.
96-20° dip.
Hard, dark brown sand-sized well-bedded basaltic volcanic tuff with about a 25° dip. (Possibly Massacre Rocks tuff).

FIGURE 2.—LOGS OF DIAMOND-DRILL HOLES 9 AND 16 NEAR EAGLE ROCK, IDAHO

Showing character of the Neeley formation with apparently infaulted beds of Massacre Rocks basaltic tuff.

include much more clay and are much lighter-colored. However, deposition in the deeper part of a lake farther from the volcanic explosions could explain this difference. Scarcity of typical lacustrine deposits indicates that Neeley Lake lay close to active rhyolitic vents. Formations A and B, overlying the Walcott indicate a revival of Neeley Lake after the Walcott tuff had been deposited.

Southward from the area in Rockland Valley coarse lump pumice and welded rhyolite tuffs are several hundred feet thick, suggesting that the vent or vents which supplied the siliceous tuffs in the Neeley lake beds probably lay in that direction. Mr. Raymond Nace of the U. S. Geological Survey called attention to a probable rhyolitic volcano shown in the air photographs north of Malad City 50 miles southeast of Eagle Rock.

Walcott welded tuff.—The Walcott welded rhyolitic tuff lies with slight disconformity on the Neeley lake beds. It was formerly called the Eagle Rock tuff (Stearns *et al.*, 1938, p. 44). Eagle Rock was used as a locality name at that time, but because a basaltic tuff originated at the Eagle Rock vent confusion can be avoided in this paper by renaming the tuff from Lake Walcott, where an excellent section of welded tuff is exposed in the east bank in the SE¼ Sec. 29, T. 8 S., R. 30 E. (Pl. 3, fig. 2).

The Walcott tuff, where not eroded, in most places is 50–70 feet thick and has four easily recognizable phases. The top (Phase 1) is a dark-red brittle pitchstone and ranges from a few inches to 2 feet thick (Pl. 5, fig. 2). It is underlain by a fine-grained pink and gray rock (Phase 2) honey-combed with lithophysae reaching 2 inches across (Pl. 2). It is commonly 30–60 feet thick. It grades downward into a fine-grained gray to pink dense rock containing few to no lithophysae. Phase 3 is a hard banded black obsidian 3–7 feet thick commonly full of spherulites an eighth to a quarter of an inch across. Under the obsidian is a few inches to a few feet (Phase 4) of black well-bedded glass shard tuff grading downward to loose white and gray ash. The whole deposit is a typical welded tuff deposited from a hot avalanche or a nueé ardente. The white ash at the bottom is interpreted as the quickly chilled phase of the fiery cloud in contact with the cold ground.

TABLE 1.—COMPARISON OF TWO OUTCROPS OF WALCOTT FORMATION

Outcrop SE¼ sec. 29 (Pl. 1)*	Outcrop near American Falls dam (outside map area)
	Basalt of unknown source
Unconformity	
Formation A	Locally, patches of Formation A
Slight disconformity	
Red welded tuff 18″	Red welded tuff locally present
Black welded tuff 2″	
Black spherulitic welded tuff with lithophysae. Spherulites up to 1¼ inches in diameter concentrated in middle 6 feet of zone. Matrix shows perlitic structure 10′	Black welded tuff with spherulites and lithophysae up to 2½ in diameter. 10–20′
Black nonspherulitic welded tuff. Contains feldspar crystals. Subconchoidal fracture 10″	Massive nonspherulitic welded tuff. 4′
Reddish-brown welded tuff identical with above 18″	
Poorly consolidated unwelded tuff, "salt and pepper" 18″	Poorly consolidated unwelded tuff, "salt and pepper". 1′
Pinkish tuff, unconsolidated 6′	White and buff unwelded and poorly consolidated well-sorted and pisolitic tuffs. Individual beds ¼ inch to 2 inches thick. 4.5′
Slight disconformity	
Neeley lake beds	Neeley lake beds

* Gradational changes only between layers.

Neeley Lake must have been drained when the tuff fell as there is no sign of subaqueous chilling, and the top of the tuff has been subaerially eroded.

Formation A.—Directly on the Walcott tuff is a firm pink sediment 2–10 feet thick, chiefly

reworked siliceous ash, deposited in shallow water. The red phase of the Walcott tuff shows erosion and slight oxidation prior to burial by Formation A. Faults displace the Walcott tuff and not Formation A. Blocks of red welded tuff and pellets of obsidian are commonly scattered through the sediment indicating local erosion of the top of the Walcott tuff. In one place well water-worn pebbles up to 1½ inches across of siliceous tuff and pumice were found in the formation. Secondary carbonates have permeated the sediment and are partly responsible for its ability to stand in vertical exposures (Pl. 3, fig. 1). It is not differentiated on Plate 1 because it has no horizontal width. The sublacustrine character of Formation A indicates the revival of Neeley Lake.

Formation B.—Formation A is overlain with slight disconformity by Formation B, thin-bedded hard brown palagonitized basaltic lapilli tuff and tuff breccia carrying scattered large accidental ejecta up to 2 feet across (Pl. 4, fig. 1). The ejecta indicate that the vent was probably not far away. A 10-inch block of Walcott tuff causes a typical bomb sag in the bedding in the gully in the SE¼ Sec. 29. Formation B is 5–25 feet thick and can be traced along the south wall of Snake River throughout most of the area. It was not differentiated on Plate 1 because it forms only vertical outcrops. It contains numerous diatomaceous interbeds usually less than 2 inches thick indicating sublacustrine deposition. Formation B is apparently an early phase of the Massacre volcanics and probably came from Massacre Rocks vent.

Massacre volcanics (Formation C).—The Massacre volcanics comprise the whole gamut of basaltic rocks—dikes, agglutinated cinder tuffs, cinder beds full of large accidental and accessory ejecta, lava flows, tuff breccias, and tuffs. They were named and mapped by Stearns *et al.* (1938, p. 46). Their principal vent was at Massacre Rocks 1¼ miles southwest of the area mapped (Fig. 1). In this earlier work, other sources for the Massacre volcanics were not recognized, but the present study has shown that another principal vent was Eagle Rock and probably some of the dikes in the area. The Eagle Rock vent probably was situated at the dikes forming the islands in the river near by and/or in the depression adjacent to the islands in the southern bank of Snake River. The depression is a result of erosion by the river in recent time, but lava dips toward the depression from all sides, and a drill hole in the center encountered only dense rock for 96 feet. It is impossible in the field always to differentiate the explosion debris from the vents so the basaltic volcanics from the Eagle Rock volcano are mapped with those from the Massacre Rocks vent. However, the Eagle Rock eruption was definitely later than the one at Massacre Rocks, and their pyroclastics can be

---

PLATE 2.—WALCOTT WELDED TUFF NEAR AMERICAN FALLS DAM, IDAHO

FIGURE 1.—WALCOTT TUFF AT AMERICAN FALLS DAM

The massive spherulitic welded tuff has a maximum thickness of 18 feet, but 300 yards to the south it is only 10 feet thick. The welded tuff is overlain here by a thin layer of Formation A and by massive basalt of unknown source.

FIGURE 2.—SPHERULITIC WELDED TUFF AT AMERICAN FALLS DAM

FIGURE 3.—LITHOPHYSAE AND SPHERULITES IN WALCOTT TUFF, NEAR AMERICAN FALLS DAM

The largest lithophysa is 2½ inches in diameter

(Photos by A. Isotoff)

PLATE 3.—ROCKS EXPOSED IN SNAKE RIVER CANYON, IDAHO

FIGURE 1.—LOOKING UPSTREAM FROM VIEWPOINT IN SW¼ SEC. 22, T. 8 S., R. 30 E., NEAR AMERICAN FALLS, IDAHO

Showing remnants of ancient Cedar Butte lava dam. (Photo by H. T. Stearns.)

FIGURE 2.—LOOKING UP LAKE WALCOTT FROM VIEWPOINT SE¼ SEC. 29, T. 8 S., R. 30 E., SHOWING STRATIGRAPHIC SEQUENCE

1. Massacre basaltic tuffs; 2. Formation B; 3. Formation A; 4. Walcott tuff; 5. Neeley lake beds; 6. Raft lake beds; 7. Eagle Rock. (Photo by H. T. Stearns.)

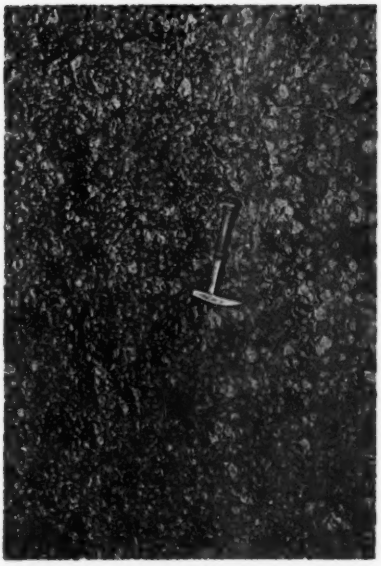


FIGURE 2

FIGURE 3

FIGURE 1

WALCOTT WELDED TUFF NEAR AMERICAN FALLS DAM, IDAHO

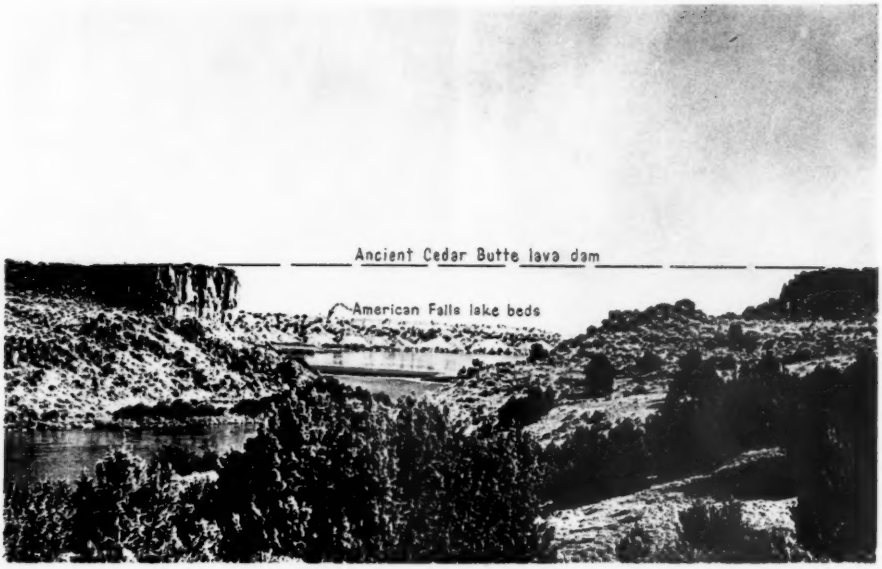


FIGURE 1

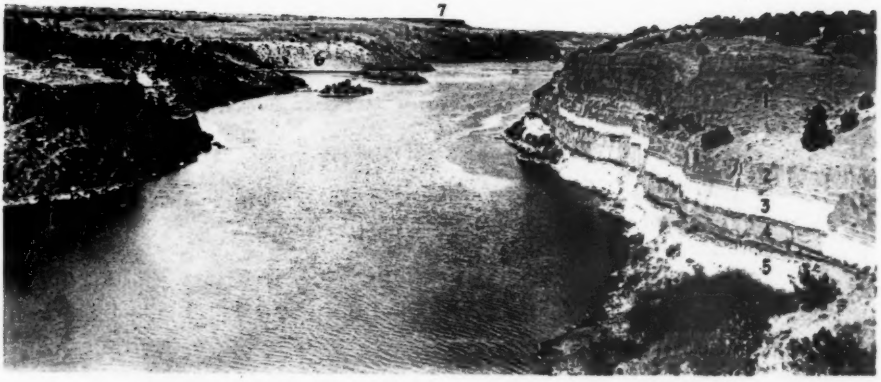


FIGURE 2

ROCKS EXPOSED IN SNAKE RIVER CANYON, IDAHO

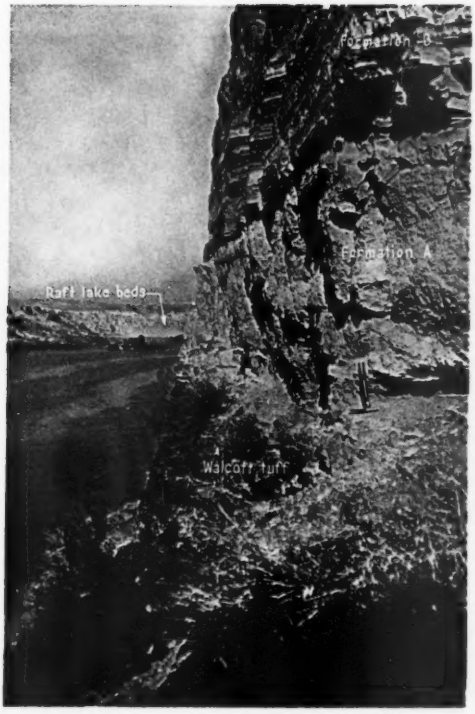


FIGURE 1

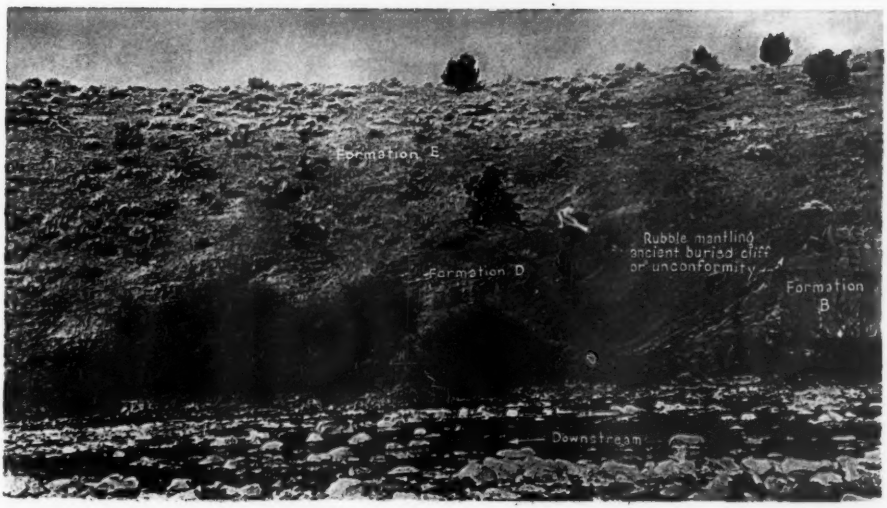


FIGURE 2

TYPICAL EXPOSURES OF FORMATIONS A, B, D, E, AND WALCOTT TUFF NEAR EAGLE ROCK, IDAHO

FIGURE 1

FIGURE 2

FAULTING IN WALCOTT TUFF NEAR EAGLE ROCK, IDAHO

differentiated by the accidental ejecta. The Massacre Rocks tuffs contain blocks of flow rhyolites and apparently do not include blocks of spherulitic welded tuff although nonspherulitic welded tuff is abundant. The absence of the spherulitic tuff in the Massacre Rocks tuff corroborates the observed southwest thinning of this phase of the Walcott tuff.

The Massacre tuffs and tuff breccias are hard where cemented by secondary carbonates which are most abundant where the tuffs originally had relatively low permeability. Elsewhere they are friable and uncemented. All beds probably were subjected to the same percolating carbonate-rich water, but the open-textured beds did not retain the carbonates. Calcareous concretions are numerous including an unusual cinder bed full of concretionary balls in the river bank below and a little upstream from Eagle Rock. The accidental and accessory ejecta range up to 3 feet across and are chiefly blocks of the Neeley and Walcott formations indicating shallow explosions. The accidental ejecta and widespread tuff-breccia beds indicate some catastrophic explosions with the usual firefountaining. It is believed that the vents erupted in a shallow lake and the explosions resulted from the contact of water with the magma.

The lava flows and dikes associated with the Massacre volcanics are typical of those formed close to vents. They carry considerable cinders and other ejecta which fell into the lava while it was still fluid. Others like the outlier along the highway in sec. 28 and the bed in the bank northeast of Eagle Rock (Fig. 3) consist of agglutinated basaltic cinders. These flows formed where semicooled clots fell in such abundance and on such a slope as to weld and flow. Such lavas are always close to vents.

The dike which crops out in the river bank west of the center of sec. 28 gave rise to a short thin flow which dips 10° NE. The dikes forming the island near Eagle Rock and cropping out in the west bank of the river near by are filled with pockets of clinker and cinder and are very irregular, indicating that they were erupting at this level. Some of the lava islands south of Eagle Rock may be lava from unknown vents. The basalt flow crossing the highway in sec. 22 rests on Massacre volcanics with apparent conformity and is an ophitic lava similar to that at Massacre Rocks vent. It is 5 feet thick, but some of it has been eroded. It has pipestem vesicles 1 foot long at the basal contact. The basalt in the north bank at American Falls previously described (Stearns *et al.*, 1938, p. 47) as possibly poured out of Massacre Rocks vent is now believed to belong to a different group of volcanics. The upper lava flow at the mouth of Rock Creek (not shown on Pl. 1) 2 miles south of the area is an ophitic basalt which issued from Massacre Rocks vent. The basalts of the Eagle Rock vent are not ophitic,

---

PLATE 4.—TYPICAL EXPOSURES OF FORMATIONS A, B, D, E, AND WALCOTT TUFF NEAR EAGLE ROCK, IDAHO

FIGURE 1.—TYPICAL EXPOSURE OF PINK TUFFACEOUS (SILICEOUS) SILT BED (FORMATION A) OVERLYING THE WALCOTT TUFF AND UNDERLYING FORMATION B IN LEFT BANK OF SNAKE RIVER ABOUT 1 MILE DOWNSTREAM FROM EAGLE ROCK DAMSITE
(Photo by Carl Tappan)

FIGURE 2.—RUBBLE AT BASE OF FORMATION D MANTLING UNCONFORMITY OR ANCIENT BURIED CLIFF IN RIGHT BANK OF SNAKE RIVER, 1200 FEET NORTH-NORTHEAST FROM EAGLE ROCK
(Photo by Carl Tappan)

PLATE 5.—FAULTING IN WALCOTT TUFF NEAR EAGLE ROCK, IDAHO

FIGURE 1.—UPTURNED BLOCK OF WALCOTT WELDED TUFF IN LEFT BANK OF SNAKE RIVER OPPOSITE EAGLE ROCK
(Photo by Carl Tappen)

FIGURE 2.—REGIONAL FAULT DISPLACING WALCOTT TUFF AND OVERLYING BEDS IN GULCH IN SW¼SW¼ SEC. 28, T. 8 S., R. 30 E.

(1) Red welded tuff, the top phase, and (2) spherulitic black glassy phase of the Walcott tuff. A. Formation A; B, Formation B. Right side is east or upthrown side of fault. (Photo by H. T. Stearns)

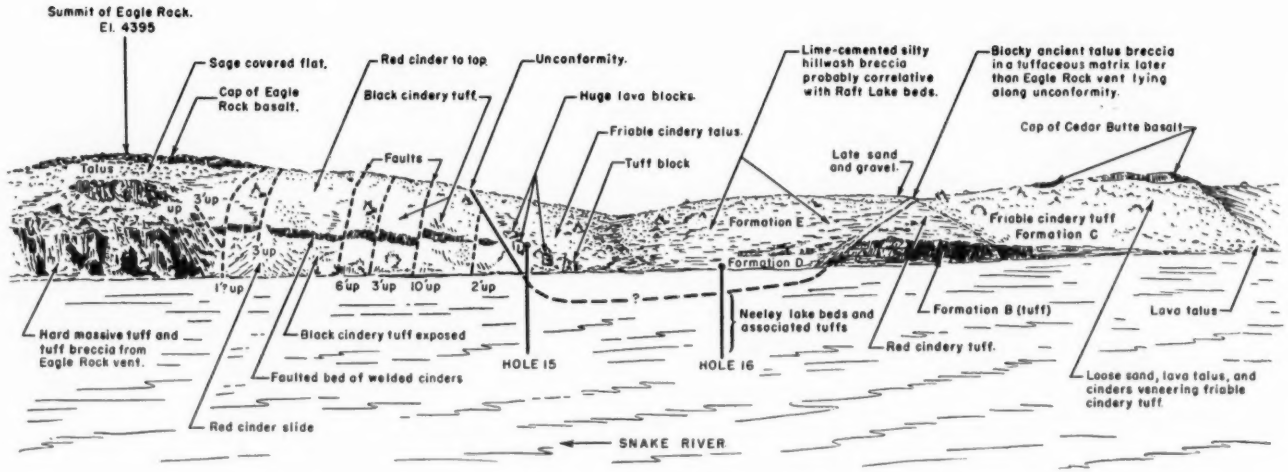


FIGURE 3.—GEOLOGIC SKETCH OF THE RIGHT BANK OF SNAKE RIVER NEAR EAGLE ROCK, IDAHO
Drawn from a photograph by Stanley Stearns

hence are readily differentiated from the diabasic-appearing basalts erupted by Massacre Rocks.

Upper Pliocene (?) Rocks

Formation D.—Mantling the sides of an ancient depression, possibly a valley cut into the Massacre volcanics, 1200 feet north-northeast from Eagle Rock in the south bank of Snake River is a friable calcareous-cemented cindery talus rubble (Pl. 4, fig. 2). It may have been due to collapse adjacent to Eagle Rock vent. The depression is 125 feet deep (Fig. 3) and contains about 50 feet of the rubble. The rubble thins to 10 feet on the east side of the unconformity 85 feet above the river. There it is a firm coarse breccia containing blocks up to 2 feet across of Walcott tuff, Neeley lake beds, and old basalts in a sparse matrix of basement rock fragments and cinders. On the west side it contains blocks 10 feet across of agglutinated basaltic tuff and other debris. It is obvious the entire deposit was derived as slope wash and talus from the Massacre volcanics bordering the depression. It contains many irregular calcareous concretionary masses and is believed to be the basal breccia of the Raft lake beds which apparently interfinger with and overlie it (Pl. 4, fig. 2).

Raft lake beds (*Formation E*).—A series of sandy and clayey sediments containing lenses of pebbles and full of calcareous concretions and thin hardpan layers lies unconformably on all the older rocks in the area. These beds are the Raft lake beds (Stearns *et al.*, 1938 p. 48) and extend for many miles downstream along the south side of Snake River (Pl. 3, fig. 2). Their lithology indicates they were laid down in a playa lake by ephemeral shifting streams which at times advanced across the playa. Tuffs, so abundant in all underlying deposits, are notably absent indicating that the frequent catastrophic volcanic eruptions had ceased. Reworked debris from the older volcanics is present but not dominant.

The Raft lake beds (Pl. 1) extend under most of the older alluvium shown on the west side of Snake River and probably also for some distance farther under the Cedar Butte basalt. The basalt appears to have spread southeastward over a rolling terrace of these beds. The beds dip toward Snake River and thin southward. They may be uplifted sediments laid down in the eastern end of the once-extensive Pliocene Lake Idaho. However, no physical connection exists between the Raft lake beds and the Hagerman lake beds, the nearest formation in the Idaho group; hence, until fossils are found, their age is uncertain.

Extensive recent studies by the senior writer in southwestern Idaho have shown that few, if any, eruptions of siliceous lavas occurred in Idaho during the existence of Lake Idaho. Basaltic volcanism had also waned greatly since late Miocene time and was vastly less than in the Pleistocene after the lake had drained. It seems best, therefore, to assign the Raft lake beds tentatively to the upper Pliocene since both they and the Idaho beds were laid down during an epoch of greatly decreased volcanic activity rather than to the middle Pliocene (?) as formerly (Stearns *et al.*, 1938, p. 48).

Pleistocene Rocks

Cedar Butte basalt.—Two buttes, one unnamed and one called Cedar Butte, in secs. 22, 23, 26, and 27, T. 8 S., R. 29 E., 4 miles west of the area gave vent to a voluminous olivine basaltic lava flow which filled a valley of Snake River many miles long. It impounded a a lake 40 miles long and 12 miles wide which extended from the lava dam (Pl. 3, fig. 1) nearly to the present town of Blackfoot. The basalt forms a rimrock 25–100 feet thick along the western bank of Snake River except around the north and west sides of Eagle Rock where it has been eroded by the overflow waters of the lake during the early phases of downcutting. The rock is black on the surface and exhibits the usual ropy skin and pressure ridges typical of the late Pleistocene lava flows in the Snake River Plains. The rock was so permeable that most of the water of the lake leaked through the dam to escape in springs at the downstream end. The springs formed numerous deep coves but when Snake River finally cut a channel through the Eagle Rock area the lake was drained, the water table dropped, and the coves were abandoned. These lie 6 miles southwest of the area and are known as the Lake

Channel country. The geologic history of these coves has already been given (Stearns *et al.*, 1938, p. 144). On Plate 1 the boulder bar shown on the downstream side of the ancient lava dam is composed of huge round basalt boulders left when the flood waters destroyed the dam.

American Falls lake beds.—The lake impounded by the Cedar Butte basalt did not drain until it was filled with sediments. Only the southwesternmost part of the formation crops out in the area mapped (Pl. 1). The sediments consist of light-colored clay, weakly consolidated silt, and sand in fairly even beds (Pl. 3, fig. 1). Locally pebble lenses occur especially near the top, and one bed of basaltic tuff 6 feet thick and 60 feet below the top crops out southwest of American Falls. The lake beds have an exposed thickness of more than 100 feet but are probably much thicker. A more detailed description has been published (Stearns *et al.*, 1938 p. 69).

Late Pleistocene and Recent Deposits

Loose sand and gravel deposits veneer the abandoned channel of Snake River on the north side of Eagle Rock (Pl. 1) where they are at least 10–20 feet thick. Forty feet above the river a distinct terrace of large basalt cobbles and boulders lies on the east bank of the river opposite Eagle Rock. A drill hole indicates that this deposit is 25 feet thick. The terrace appears to mark a distinct halt in the downcutting of Snake River during the late Pleistocene.

Younger alluvium forms benches and bars along the river. It is everywhere thin because in low water the river floor is bare rock. Locally it has been placer mined for gold and probably reaches a maximum thickness of 20 feet.

The prevailing strong southwesterly winds have formed local dunes 2–10 feet high. The sand has filled the interstices in many of the talus slopes. It was not mapped separately.

Structure

The Tertiary beds in general lie essentially horizontal or dip gently toward the axis of the Snake River Valley. The Massacre volcanics have steep dips around Eagle Rock vent, and in the southwestern part they dip gently away from the Massacre Rocks vent. Superimposed on these local structures are gentle synclinal and anticlinal structures indicating compression during the late Tertiary in common with beds of similar age in southwestern Idaho. The axes of the folds are shown on Plate 1 in sec. 21. Block faults, mostly with small displacements, are numerous and in the vicinity of Eagle Rock vent are too close together for mapping but are shown in Figure 3. They probably represent local collapse around the vent after the eruptions ceased. Regional faults are present also as the Walcott tuff and Neeley lake beds are broken into narrow blocks all the way upstream to American Falls (Stearns *et al.*, 1938, Pl. 6). Three such faults are shown on Plate 1. The one that crosses the river just upstream from the island in the eastern part of sec. 21 has a downthrow of about 25 feet on the east side and drops the Walcott tuff below river level.

A second fault with a throw of at least 50 feet down to the northeast cuts across the river from the left bank near Eagle Rock (Pl. 1). This fault or group of faults is evidenced by an upturned block of Walcott tuff (Pl. 5, fig. 1). The block extends above the bottom of the same formation near by which suggests a reverse fault. The upturned block can be traced part way across the river where it is buried by large loose rocks. The faulting took place while the overlying Formation B was unconsolidated, for the latter is highly distorted but not brecciated. The faulting tilted the underlying Neeley lake beds also and exposed them at the surface. A clinkery basaltic dike crops out for 10 feet above the river on the downstream side of the block. The clinkery character of the dike, which stops abruptly in the lake beds, indicates that it was nearly at the surface at the time of eruption. Fused Neeley lake beds are present in the irregular surface.

In a small gulch draining into Lake Walcott on the west side of Highway 30 N. in the SW¼ sec. 28 is a fault which displaces the Walcott tuff 2 feet without disturbing the overlying Formation A. A third regional fault is well exposed 25 feet to the east, and it displaces Formations A and B (Pl. 5, fig. 2). It trends nearly north and drops the Walcott tuff and associated beds 15 feet on the west side. This fault runs into the river and probably extends

for some distance upstream under the later volcanic debris from Eagle Rock vent.

Two other major breaks in the stratigraphy have been tentatively interpreted as erosional unconformities, but the evidence is meager. The Massacre tuffs are terminated by a buried cliff 80 feet high in the south bank of the river opposite the island in sec. 21 and just upstream from a regional fault. The cliff faces north and may be a canyon wall rather than a fault scarp. A similar break exists in the east bank just upstream at the bend in the river. There the Walcott tuff is again on the lower or northerly side.

A similar break of about 80 feet can be seen just under the scenic viewpoint in the southeast corner of sec. 29 where the Massacre volcanics mantle a scarp (possibly a fault cliff or a canyon or crater wall) terminating the Neeley lake beds, the Walcott tuff, and Formations A and B (Fig. 4). A fault with a 2-foot downthrow to the east parallels the buried scarp. The same ancient scarp crops out again in a small gulch to the south close to the highway (Pl. 1). There Formation B shows mantle bedding on blocks of Phase 1 of the Walcott tuff where they lie on top of Formation A. Some of the blocks are 18 inches across.

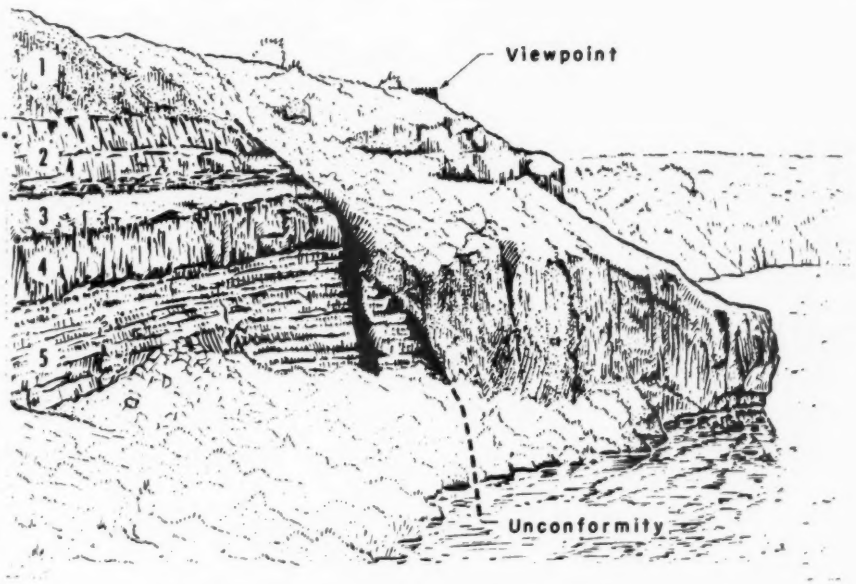


FIGURE 4.—SKETCH SHOWING EITHER AN UNCONFORMITY OR A FAULT TERMINATING NEELEY LAKE BEDS, WALCOTT TUFF, AND FORMATIONS A AND B

Drawn by Stanley Stearns from a photograph

1. Massacre Rocks basaltic tuff breccia, same as that at right of unconformity.
2. Formation B, a thin-bedded basaltic sublacustrine basaltic tuff.
3. Formation A, a siliceous ashy shallow-lake deposit.
4. Walcott tuff.
5. Neeley lake beds, chiefly siliceous ash beds at this exposure.

No faults were observed in the later formations, but the weak Raft lake beds make faults difficult to find. The faulting and warping is obviously pre-Pleistocene as neither affects the Cedar Butte basalt or the American Falls lake beds.

GEOLOGIC HISTORY

Tertiary Time

(1) Deposition of Neeley lake beds and associated volcanic tuffs. This lake was ephemeral and occupied a depression in the Snake River Plain at least from American Falls to Massacre

Rocks and probably over a much greater area. Pink tuffs and tuffaceous rhyolitic sandstones constitute the major part of the formation encountered by drills. Pale-buff clays and thin fresh-water marly limestones are interbedded with the volcanic ashes. The whole series accumulated in a basin receiving direct ash falls from several volcanoes. During periods of quiescence, streams washed the loose ash from the drainage areas into the basin where a shallow playa lake or series of lakes existed.

(2) Uplift, draining of Neeley Lake, and probably slight erosion.

(3) Deposition from a hot glowing ash cloud, in a matter of minutes, of the Walcott rhyolite tuff which is now mostly welded to hard lithophysae and spherulitic obsidian in beds 10–65 feet thick (Pl. 2; Pl. 5, fig. 1). The Walcott formation has been separated into four phases in the logs as follows from top to bottom: (Phase 1) red welded tuff 1–2 feet thick; (Phase 2) gray honeycomb type (lithophysae) grading downward to very hard type with scarce holes, 50± feet thick; (Phase 3) obsidian, containing buckshotlike spheres (spherulites) in the upper part, 2–4 feet thick; and (Phase 4) black and gray ash (unwelded) ½ to 3± feet thick.

(4) Faulting, local erosion, and possibly some gentle folding.

(5) Deposition of 2–10 feet of pink compact ashy (siliceous) silt which contains scattered blocks of slightly weathered red welded tuff (Phase 1) of the Walcott tuff and grains of obsidian. The deposit contains diatoms and indicates a revival of Neeley Lake. It is herein designated Formation A (Pl. 4, fig. 1).

(6) Deposition of 5–25 feet of hard brown basaltic lapilli tuff in thin layers, alternating with thin beds of diatomaceous sediments containing rhyolitic ash. Ejecta of basement rocks are common, and scattered blocks 2 feet across indicate the vent was not far away. The beds appear to be the oldest pyroclastics from the Massacre Rocks vent and are herein designated Formation B (Pl. 4, fig. 1).

(7) An apparent erosional interval when steep-sided canyons 200 feet or more deep were cut. No evidence was found of an erosional interval on the top of the tuff described in epoch 6 in the exposures between the supposed canyons; hence the steep unconformities may be the result of faulting. Drag dips, however, are lacking at the unconformities, and debris overlying the contact appears to show gravity sorting. Both of these conditions support the erosional hypothesis. Possibly this epoch separates the Eagle Rock volcanics from the Massacre Rocks volcanics.

(8) Cataclysmic explosions at Massacre Rocks vent (2½ miles downstream from Eagle Rock) and subsequently from Eagle Rock vent. Vast quantities of basaltic cinders and fragments of basement rock were scattered more than 20 square miles. Some of the beds are cinders, indicating intense fire fountains, but many are vesicular glassy lapilli mixed with fragments of the Walcott and Neeley beds, cemented chiefly by infiltered carbonates into firm tuffs and tuff breccias. Thin interbeds of blue and red basalt occur, and two beds of welded cinders lie close to the vents. The Massacre volcanics form most of the banks of Snake River in this area. The cindery tuff, tuff breccia, and agglomerate deposits overlying Formation B are herein designated Formation C. Local collapse around Eagle Rock vent caused numerous small faults.

(9) A period of faulting, gentle folding, followed by considerable erosion.

(10) Deposition of cinders, huge blocks of Eagle Rock basalt, and abundant large blocks of basement rocks as talus in a depression of unknown origin about 125 feet deep and 400 feet wide just upstream from Eagle Rock (Fig. 3). The debris is now poorly cemented with carbonates and is designated herein as Formation D (Pl. 4, fig. 2). The ancient buried cliff exposed by erosion and bounding the upstream side of the depression is shown in Figure 2 of Plate 4. Erosion also destroyed much of the south side of Eagle Rock cone.

(11) Deposition of the Raft lake beds which extend for miles along the south side of Lake Walcott Reservoir and across the mouth of Rockland Valley. Numerous calcareous concretions occur in the gulches eroded in the formation. Beds of silt dominate, with lesser amounts of clay and pea gravel. Lenses of calcareous-cemented debris locally carrying cinders and other debris washed from the Massacre volcanics are common in this area.

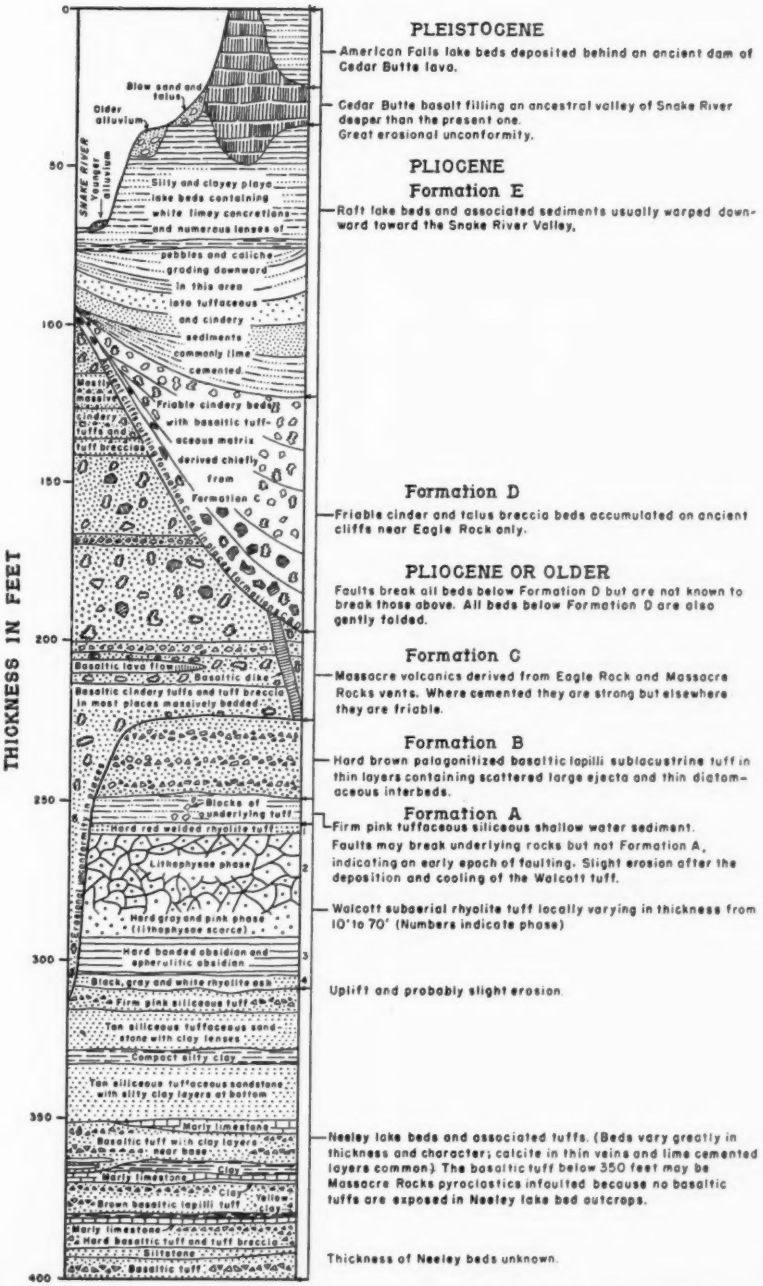

THICKNESS IN FEET
0
50
100
150
200
250
300
350
400
PLEISTOCENE
American Falls lake beds deposited behind an ancient dam of Cedar Butte lava.
Cedar Butte basalt filling an ancestral valley of Snake River deeper than the present one.
Great erosional unconformity.
PLIOCENE
Formation E
Raft lake beds and associated sediments usually warped downward toward the Snake River Valley.
Formation D
Friable cinder and talus breccia beds accumulated on ancient cliffs near Eagle Rock only.
PLIOCENE OR OLDER
Faults break all beds below Formation D but are not known to break those above. All beds below Formation D are also gently folded.
Formation C
Massacre volcanics derived from Eagle Rock and Massacre Rocks vents. Where cemented they are strong but elsewhere they are friable.
Formation B
Hard brown palagonitized basaltic lapilli sublacustrine tuff in thin layers containing scattered large ejecta and thin diatomaceous interbeds.
Formation A
Firm pink tuffaceous siliceous shallow water sediment.
Faults may break underlying rocks but not Formation A, indicating an early epoch of faulting. Slight erosion after the deposition and cooling of the Walcott tuff.
Walcott subaerial rhyolite tuff locally varying in thickness from 10' to 70' (Numbers indicate phase)
Uplift and probably slight erosion.
Neeley lake beds and associated tuffs. (Beds vary greatly in thickness and character; calcite in thin veins and lime cemented layers common.) The basaltic tuff below 350 feet may be Massacre Rocks pyroclastics infaulted because no basaltic tuffs are exposed in Neeley lake bed outcrops.
Thickness of Neeley beds unknown.
Blow sand and talus
Older alluvium
SNAKE RIVER
Younger alluvium
Silty and clayey playa lake beds containing white limey concretions and numerous lenses of pebbles and caliche grading downward in this area into tuffaceous and cindery sediments commonly lime cemented
Friable cindery beds with basaltic tuffaceous matrix derived chiefly from Formation C
Massive cindery tuffs and tuff breccias
Basaltic lava flow
Basaltic dike
Basaltic cindery tuffs and tuff breccia in most places massively bedded
Blocks of underlying tuff
Hard red welded rhyolite tuff
Lithophysae phase
Hard gray and pink phase (lithophysae scarce)
Hard banded obsidian and spherulitic obsidian
Black, gray and white rhyolite ash
Firm pink siliceous tuff
Tan siliceous tuffaceous sandstone with clay lenses
Compact silty clay
Tan siliceous tuffaceous sandstone with silty clay layers at bottom
Marly limestone
Basaltic tuff with clay layers near base
Clay
Marly limestone
Clay
Yellow clay
Brown basaltic lapilli tuff
Marly limestone
Hard basaltic tuff and tuff breccia
Siltstone
Basaltic tuff
1
2
3
4

FIGURE 5.—COMPOSITE STRATIGRAPHIC SECTION OF EAGLE ROCK AREA, IDAHO

The beds are transitional downward into Formation D indicating that D is a local bottom phase of this epoch of deposition.

Pleistocene Time

(12) A long period of erosion and deformation, during which probably a wide ancestral Snake River Valley was cut in the weak Raft lake beds 2 miles or more north of the area. Eagle Rock cone was further eroded.

(13) Eruption of a voluminous flow of basalt from Cedar Butte cone a few miles northwest of the area. The basalt spread westward, southward, and eastward displacing Snake River about 55 miles from near Blackfoot to a point near the mouth of Indian Creek. It created the ancestral American Falls lake 40 miles long and 12 miles wide which was damned by the lava a mile upstream from Eagle Rock. The lake leaked through the lava to form numerous large springs and coves now abandoned and known as the "Lake Channel" 6 miles southwest of the area.

(14) Deposition of the buff clays, silts, sands, and gravels in the depression behind the lava dam, called the American Falls lake beds.

Pleistocene and Recent Time

(15) Overtopping of the lava dam and the formation of numerous flood channels by Snake River during the downcutting cycle and the deposition of alluvium. One such channel was cut around the northwest side of Eagle Rock. Much of the Raft lake beds was swept away, and finally the river cut down into the ancient Pliocene rocks exposing complex faults and gentle folds. Several boulder terraces and bars now 25–50 feet above the river are deposits left as Snake River cut downward to its present channel. These older sand, gravel, cobble, and boulder deposits well above the present-day flood stages of the river constitute the older alluvium. The young alluvium is the debris left by the present river during flood stages.

Petrography

The petrography of the Walcott (formerly Eagle Rock) welded tuff was briefly described by M. N. Short (Stearns *et al.*, 1938, p. 44). A more detailed description of a similar formation in Ammon quadrangle near Idaho Falls has been published (Mansfield and Ross, 1935).

NEELEY LAKE BEDS: The Neeley lake beds consist of tuffaceous silts, claystones, and marls; individual beds range from a few inches to more than 5 feet thick.

Microscopic examination of the calcareous and clay facies of the formation shows the presence of fresh-water sponge spicules. The skeleton spicules average about .3 mm in length and .012 in the thickest cross section. They are slightly curved and sharply terminated. Some are smooth, others are sparsely spined. Associated with them are two types of minute gemmule spicules. Some are slightly curved spinose cylinders; others are spool-like with spinose stems and ends. At least two genera are present, and these most closely resemble *Spongellia* and *Dosilia* (Ward and Whipple, 1918, p. 306–315). No other recognizable fossils have been found, and the sponge spicules are not diagnostic.

WALCOTT FORMATION: The lower 6–8 feet of the Walcott formation consists of beds of volcanic ash and dust ranging from a quarter of an inch to 6 inches thick. Many of the thicker beds are pisolitic, and all show excellent sorting. Crystals and lithic fragments are rare. Glass shards have an index of refraction near 1.496. These beds grade upward through compacted ash into welded tuff (Pl. 2, fig. 1). The latter ranges from 6 to 18 feet in thickness in the measured outcrops but shows the same sequence of zones. The lower and upper zones are pitchstonelike, black or red-brown massive welded tuffs which break readily into slightly curved slabs. The middle zone is crowded with spherulites and lithophysae ranging from a quarter of an inch to 2½ inches in size and set in a glassy matrix with pronounced perlitic fractures (Pl. 2, figs. 1, 2).

In the welded phase of the formation the microscope shows vermiform structure produced from collapsed and tightly compressed bubbles of glass. The radiating needles of feldspar which constitute the spherulites in general transgress the structure but squeezing of the glass shards between adjacent spherulities has been noticed. This would indicate that the shards were plastic at the time of development

of spherulites. Some of the spherulities have grown from nuclei of oligoclase, magnetite, or augite, but in most cases nuclei are lacking.

All sections of the welded tuff show aggregate polarization resulting from the development of fibrous feldspar normal to the walls of the collapsed ash particles. The refractive index of the glass shards throughout the formation is near 1.496. The crystal fragments in order of abundance are oligoclase, sanidine, quartz, augite, magnetite, and green hornblende. Among rare lithic fragments are rhyolitic pumice and glassy basalt.

These welded tuffs are similar to the tuffs of the Ammon quadrangle (Mansfield and Ross, 1935) except for the absence of the lithoidal phase in the outcrops of the Walcott formation.

FORMATION A: Samples taken from several levels above the contact with the Walcott formation were examined in powder and found to consist of sharp shards of rhyolitic glass (av. R.I. 1.495), scarce crystal fragments, and fragments of the upper phase of the Walcott tuff. Well-preserved tests of diatoms were noted, and separation in bromoform diluted to sp. gr. 2.3 yielded from 6 to 20 diatom tests per cc of powder. The abundance of diatoms increases toward the top of the bed. The diatoms have been tentatively identified as *Melosira* and *Cosinodiscus*. It is concluded that Formation A represents ash reworked by a lake.

FORMATION B: Formation B consists of alternating beds of rhyolitic and basaltic tuff deposited in a lake. The beds, ranging from less than an inch to 8 inches thick, rest upon the underlying Formation A with a very slight disconformity. The greater resistance of the basic layers to erosion gives the impression of a far greater break than actually exists.

The beds of rhyolitic ash are identical in composition with those of Formation A except for greater abundance of diatoms. Some of them, in fact, may be called impure diatomites. The basaltic tuffs consist of sideromelane (R.I. 1.569), some of which has changed to fibropalagonite and opal. Accidental ejecta include crystals of plagioclase, quartz, hornblende, and magnetite, and fragments of nonspherulitic welded tuff, basalts, and black siliceous vitrophyre. The vitrophyre occurs as frequent inclusions in the pyroclasts in the immediate vicinity of Massacre Rocks vent and has not been found among the ejecta of Eagle Rock vent.

The basic tuffs are regarded as the product of a weak, spasmodic activity of Massacre Rocks vent, while the interbedded rhyolitic tuffs are identical with the material of Formation A and are considered as representing similar re-worked ash deposited between eruptions.

TABLE 2.—ACCIDENTAL EJECTA FROM FORMATION C

In pyroclasts from Massacre Rocks vent	In pyroclasts from Eagle Rock vent
Fragments of Neeley formation	Fragments of Neeley formation
Basalt from unidentified source	Basalt from unidentified source
Porphyritic rhyolites	Absent
Black vitrophyre	Absent
Nonspherulitic welded tuff	Nonspherulitic welded tuff
Absent	Spherulitic welded tuff

MASSACRE VOLCANICS (FORMATION C): The thinly bedded Formation B grades upward into massive deposits of brown basaltic tuff nearly 50 feet thick. Apart from the absence of palagonite and the larger size of accidental ejecta the tuff is identical in composition to the thin beds of basaltic tuff in Formation B. A slight disconformity separates this bed from an equally thick and massive pyroclast characterized by included blocks up to 6 feet in diameter. Conspicuous among the accidental ejecta are the black vitrophyre mentioned above and the nonspherulitic welded tuff. A third massive pyroclast also nearly 50 feet thick lies with pronounced unconformity on the preceding one. It is characterized by blocks of spherulitic welded tuff and is tentatively ascribed to the activity of the Eagle Rock vent (Table 2).

EAGLE ROCK FLOW AND DIKES: The basalt exposed on the crest of Eagle Rock and on both sides of the river in sections 28 and 29 is a flow from Eagle Rock vent. It has a red vesicular base and a dense olive-black middle phase which grades into red scoriaceous basalt at the top. Locally lenses of pyroclastic material are intercalated between flow units.

The microscope reveals clusters of plagioclase laths (up to .5 mm in length and near An_{65} and olivine grains (up to .3 mm in length and near Fo_{80}) in a very fine-grained mesostasis of plagioclase, pale-green pyroxene, and magnetite.

The basal part carries inclusions of basaltic cinders and quartz grains. Cristobalite is developed in some of the vesicles and also along cleavage cracks of the feldspar phenocrysts.

The dikes are identical with the flow basalt in texture and composition, but the olivine crystals are in part changed to iddingsite. Inclusions of welded tuff and a coarse-grained ophitic basalt from Massacre Rocks flow are rather numerous.

RAFT LAKE BEDS: Microscopic examination of Raft lake beds shows that detrital material is much more abundant than in any other sedimentary formation of the area, while glass is relatively rare. Poorly consolidated layers of the formation carry diatom shells. Much calcareous material is present throughout the formation.

CEDAR BUTTE BASALT: Cedar Butte basalt is a dark-gray basalt with conspicuous phenocrysts of fresh olivine up to 2 mm in diameter. The texture is ophitic to subophitic with laths of zoned and complexly twinned plagioclase (near AB_3 and averaging .4 mm in length) enveloped by lilac-gray titanaugite (beta near 1.730). Olivine has a 2V very near 90° and is negative. Its composition therefore is about $Fo_{78\text{-}80}$.

The accessories are ilmenite, magnetite, and apatite. In the vesicular phases buff sideromelane appears as lining of vesicles.

This basalt appears to be uniform throughout the flow.

References Cited

Anderson, A. L., 1931, Geology and mineral resources of eastern Cassia County, Idaho: Idaho Bur. Mines Bull. 14.

Kirkham, V. R. D., 1931a, Igneous geology of southwestern Idaho: Jour. Geology, v. 39, p. 564–591.

—— 1931b, Revision of the Payette and Idaho formations: Jour. Geology, v. 39, p. 193–239.

Mansfield, G. R., 1927, Geography, geology, and mineral resources of part of southeastern Idaho: U. S. Geol. Survey Prof. Paper 152, 453 p.

Mansfield, G. R., and Ross, C. S., 1935, Welded rhyolite tuffs in southeastern Idaho: Amer. Geophys. Union Trans., pt. 1, p. 308–321.

Ward, H. B. and Whipple, G. C., *in* Potts, Edward, 1918, Fresh water biology, Chapter X, The sponges (Porifera), p. 306–315: N. Y., John Wiley & Sons.

Stearns, H. T., Crandall, Lynn, and Steward, W. G., 1938, Geology and groundwater resources of the Snake River Plain in southeastern Idaho: U. S. Geol. Survey Water-Supply Paper 774, 268 p. (All geology was done by the senior author)

HOPE, IDAHO: IDAHO STATE COLLEGE, POCATELLO, IDAHO

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, JANUARY 3, 1955

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 67, PP. 35-54, 3 FIGS. JANUARY 1956

URANIUM-LEAD METHOD OF AGE DETERMINATION

PART I: LAKE ATHABASCA PROBLEM

BY WALTER R. ECKELMANN AND J. LAURENCE KULP

ABSTRACT

A suite of samples of pitchblende, clausthalite, and galena from various mines in the Lake Athabasca uranium province has been subjected to isotopic and chemical analyses as well as radon-leakage measurements in order to obtain apparent ages from the isotopic ratios Pb^{206}/U^{238}, Pb^{207}/U^{235}, and Pb^{207}/Pb^{206}. Pb^{210}/Pb^{206} measurements were made to check equilibrium in the decay series.

The apparent isotopic ages range from 220 to 1860 m.y. Alteration effects which might explain these anomalies are considered. Uranium leaching and radon leakage are inadequate to explain these anomalies.

The diverse ages can be calculated on the hypothesis of a single period of pitchblende deposition at 1.90 ± .04 b.y. ago followed by two periods of exsolution of lead at about 1.2 and .15 b.y. This is consistent with the 207/206 ratio of the radiogenic lead in the clausthalite and galena which apparently formed at the times of recrystallization. However, the existing data do not preclude more than two periods of lead exsolution.

An alternative hypothesis involving successive epochs of pitchblende deposition is more complex geologically and, without contemporaneous lead exsolution, cannot account for the observed isotopic relations. The recrystallization presumably requires only the elevation of the regional temperature to 150–300°C in the presence of water. The variable fractions of lead removed during the periods of recrystallization can be ascribed to variations in temperature and water content throughout the district.

It is quite certain that (1) the initial uranium deposition occurred about 1.9 b.y. ago; (2) there have been at least two periods of lead exsolution; (3) one period of lead exsolution must have occurred subsequent to 0.22 b.y. ago; (4) another period of lead exsolution probably occurred about 1.2 b.y. ago; (5) alteration of subsurface pitchblende has been negligible during the last million years.

These conclusions resulting from an intensive study of an important uranium province suggest some general principles which may be applied to other areas. If samples are chosen to avoid recent weathering effects and if the radon leakage is measured, the remaining anomalies in the isotopic ages are probably due to partial lead removal at some time or times during the geologic history of the mineral. In all cases the 207/206 age will be closest to the true age but will be minimal. The true age can be approximated if a large number of samples from a given locality are studied with their associated common leads.

Uranium minerals that give accordant isotopic ages have a known age and indicate the absence of significant regional thermal metamorphism following formation.

CONTENTS

TEXT

	Page
Introduction	36
Acknowledgments	37
Experimental procedures	38
Samples	40
Geological setting	40
Results	40
Chemical analyses	40
Lead isotopic assay	41
Summary of raw isotopic ages	41
Radon leakage	42
Pb^{210}	43
Possible alteration effects	43
Uranium loss	43
Radon leakage	44
Lead loss	46
Discussion	47

Page
Analysis of common-lead data 47
Apparent age of pitchblende from uncorrected isotopic ratios 49
Possible interpretations 50
Geological significance 51
Geochronological significance 51
Conclusions 52
References cited 52

ILLUSTRATIONS

Figure Page
1. Comparison of 206/238 and 206/210 ages 45
2. Effect of recrystallization on the 207/206 ratio for two periods of deposition 49
3. Histogram of reported 207/206 ages from Lake Athabasca region 50

TABLES

Table Page
1. Equations and constants used in the uranium-lead method 37
2. Description of pitchblende samples 39
3. Description of lead minerals 40
4. Chemical analyses 41
5. Reproducibility of chemical analyses 41
6. Isotopic data of pitchblende concentrates 42
7. Isotopic data of common lead in lead minerals 42
8. Effect of composition of common lead on isotopic ages 42
9. Corrected per cent of radiogenic lead 43
10. Ages uncorrected for radon leakage or leaching effects 44
11. Typical radon-leakage values 44
12. Radon-leakage corrections on isotopic ages of some representative Lake Athabasca samples 44
13. Effect of uranium loss on various isotopic ages 45
14. Effect of radon leakage on various isotopic ages 46
15. Effect of lead loss on various isotopic ages of uranium minerals at least 10 million years old 46
16. Exsolution of lead from uraninite at 290°C 47
17. Isotopic analysis of lead from clausthalite and galena concentrates, Lake Athabasca district 48
18. Time and fraction of lead removal 51

Introduction

This paper is the first in a series concerning the uranium-lead method of age determination, the primary calibration of the geologic time scale. The method serves as a basic reference for the geologic chronometers such as rubidium-strontium and potassium-argon because it involves at least two independent isotopic clocks in the same specimen. Most uranium- or thorium-bearing minerals contain three long-lived radioactive isotopes, U^{238}, U^{235}, and Th^{232} which decay at different rates and possess unique decay chains involving several chemical elements, thus permitting sensitive detection of alteration. Any set of conditions which could extract parents or daughters from the decay chain would alter the isotopic ratios such that the ages derived from these ratios would not agree. Concurrence of these isotopic ratios would suggest that an absolute age has been obtained.

The theory of the uranium-lead method of age determination has been discussed in many publications. Kulp *et al.* (1954) compiled the latest half-life data and constructed nomographs based on these new constants. Table 1 gives the basic equations and physical constants that are used in the uranium-lead method. It is seen that minerals that carry negligible thorium have two independent clocks. The apparent ages are derived from the ratios Pb^{206}/U^{238} and Pb^{207}/U^{235}. In addition to these, the ratio Pb^{207}/Pb^{206} changes with time. An age derived from this ratio is not independent of the former two but is affected by alteration in an entirely different manner.

Several dozen uranium-lead age determinations have been made on various minerals for which the complete isotopic data have been obtained (Nier, 1939; Nier *et al.* 1941; Holmes, 1947; National Research Council, 1949; Kerr and Kulp, 1952; Stieff *et al.*, 1953; Collins *et al.*, 1954; Kulp *et al.*, 1954; Wasserburg and Hayden, 1955). In only about 30 per cent of these cases did the ages derived from the three isotopic ratios agree within the experimental error. Kulp *et al.* (1954) made an attempt to evaluate the factors which might cause discordant ages among the three ratios. They concluded that the chemical and isotopic measurements are seldom the limiting factors, but caused errors on the order of tenths of per cent to a few per cent. They further demonstrated that in most cases the correction for common lead can be made with sufficient precision so

that this correction causes negligible error. In rare cases where the concentration of common lead in the total lead of a radioactive mineral is very high the error may be appreciable. It was also suggested that in some cases radon leakage was a significant source of error particularly in the younger samples. Since radon (noble gas, T-½ 3.8 days) occurs in the U^{238}/Pb^{206} decay scheme, leakage of this gas would cause the 206/238 age to be low in direct proportion to the amount of radon lost and would tend to make the 207/206 age high in a non-linear manner. The 207/206 age is very sensitive to small errors for ages less than 500 m.y. For ages greater than 1000 m.y. the effect of radon leakage is practically linear. Therefore, for older minerals a few per cent of radon leakage causes no larger an error in the 207/206 age than in the 206/238 age. Relatively little work has been done on the possibilities of leaching and alteration of either lead, uranium, or any of the intermediate products.

Since radon leakage or errors in the physical and chemical measurements could not account for the anomalous ages, it was decided to initiate a study to define the factor or factors that cause anomalous ages. An unusual opportunity presented itself when Dr. S. C. Robinson of the Canadian Geological Survey offered a carefully prepared suite of pitchblende concentrates from various mines of the Lake Athabasca district along with concentrates of the common lead minerals, galena (PbS), and clausthalite (PbSe). The Lake Athabasca district was ideal for this study because preliminary work by Collins *et al.* (1952) had shown several samples with anomalous ages. Furthermore the excellent geological studies of Dr. Robinson and his colleagues have made it possible to correlate laboratory data and field interpretation.

This research had a two-fold purpose: (1) to understand the reason for the large variations in ages obtained from different isotopic ratios in a single province, and (2) to learn as much as possible about the time or times of deposition and the subsequent history of the important uranium deposits in the Lake Athabasca district. All samples were analyzed for lead, uranium, and thorium, and the isotopic analyses were carried out on the separated lead. Radon leakage was measured on a representative number of these samples, and the Pb^{210} concentration was determined. The results were then used to construct a theory which would explain the differences in the apparent ages.

TABLE 1.—EQUATIONS AND CONSTANTS USED IN THE URANIUM-LEAD METHOD

$$\frac{N_{207}}{N_{206}} = \frac{N_{235}}{N_{238}} \frac{e^{\lambda_{235}T} - 1}{e^{\lambda_{238}T} - 1} = \frac{1}{137.7} \frac{e^{+.9722 \times 10^{-9}T} - 1}{e^{+.1541 \times 10^{-9}T} - 1}$$

$$\frac{N_{206}}{N^0_{238}} = 1 - e^{-\lambda_{238}T} = 1 - e^{-.1541 \times 10^{-9}T}$$

$$\frac{N^{207}}{N^0_{235}} = 1 - e^{-\lambda_{235}T} = 1 - e^{-.9722 \times 10^{-9}T}$$

$$\frac{N_{208}}{N^0_{232}} = 1 - e^{-\lambda_{232}T} = 1 - e^{-.4967 \times 10^{-10}T}$$

$T_{1/2}(U^{238}) = 4.51 \pm .01 \times 10^9$ yrs.

$T_{1/2}(U^{235}) = 7.13 \pm .16 \times 10^8$ yrs.

$$\frac{N_{238}}{N_{235}} = 137.7 \pm .5$$

$T_{1/2}(Th^{232}) = 1.39 \pm .02 \times 10^{10}$ yrs.

N^0_{238}, N^0_{235},—number of atoms at T = 0

N_{238}, N_{235}, etc.—number of atoms at present

ACKNOWLEDGMENTS

In large part it was the idea of Dr. S. C. Robinson that an intensive study of many samples from the Lake Athabasca district would yield large returns. In addition to preparing and submitting samples, Dr. Robinson has been most co-operative in supplying information. We have appreciated his contribution as well as those of R. J. Traill and R. K. Wanless who are associated with Dr. Robinson in the Canadian Geological Survey Laboratories. Several of the samples were obtained from the research collection of Professor P. F. Kerr, who also encouraged the undertaking of the Lake Athabasca problem.

Dr. C. B. Collins was most helpful in permitting the second author to visit his laboratory and in explaining in detail the techniques employed by the Toronto group. The lead tetramethyl was prepared by J. E. Gaetjen and R. E. Nuckolls. H. R. Owen contributed largely in the design and construction of the mass spectrometer. The tube was built in the

shops of L. C. Eichner Instruments Co. In the electronic service, scanning and calculations, the authors were assisted by W. Broecker and W. Knox. The authors wish to acknowledge the valuable and continued assistance of G. L. Bate in the mass spectrometry.

The co-operation of Dr. C. J. Rodden, Director of the Atomic Energy Commission New Brunswick Analytical Laboratory, was essential as was that of Dr. J. J. Tregoning, Chief of the General Analytical Branch.

The final interpretation of the data was derived from many discussions at various stages in the work. The authors particularly wish to mention the discussions with L. R. Stieff, T. W. Stern, R. M. Farquhar, R. D. Russell, W. Broecker, P. Gast and G. L. Bate.

The authors also wish to note that the late Dr. J. P. Marble gave major encouragement to the initiation of this uranium-lead program at Lamont.

The financial support for this work came from The Atomic Energy Commission Research Division under Contract AT(30-1)-1114. The continued help and scientific interest of Dr. D. R. Miller of the Research Division and Mrs. Muriel Mathez, and D. L. Everhardt of the Raw Materials Division of the Atomic Energy Commission has been greatly appreciated.

Experimental Procedures

The specimens that have been studied were procured as galena, clausthalite, or pitchblende. The pitchblende samples were analyzed for lead and uranium by wet chemical methods and the lead was quantitatively extracted and purified as lead chloride.

The technique used in preparing lead tetramethyl was adapted from that described by Collins and Freeman (1951). For an average sample of .10 g of lead chloride, 2 cc of anhydrous ethyl ether and 1 cc of anhydrous methyl magnesium bromide are placed in a reaction flask which utilizes a magnetic stirrer and cold finger condenser. While the liquid phase is stirred, the lead chloride is added slowly; refluxing follows for approximately 3 hours. Upon completion of the reflux, water is added to stop the reaction and to separate the ether phase containing the tetramethyl from the solid phase. Anhydrous calcium chloride is then added to the ether phase to remove any water, and the lead tetramethyl is separated by distillation of the ether at atmospheric pressure. When a liquid phase of approximately 1.5 cc remains, the sample is placed in a smaller fractionating column with a side-arm attachment. Distillation at atmospheric pressure is continued until a volume of about .1 cc is reached at which point the sample is transferred by breaking the tip at the base of the fractionating column and by allowing the remaining liquid phase to enter the sample container. The ether is removed by stepwise procedure at reduced pressure until the vapor pressure of the sample becomes that of the lead tetramethyl. Samples of less than .1 g of lead chloride have been prepared successfully yielding enough tetramethyl for several 1-hour runs in the mass spectrometer.

The mass spectrometer employed in these studies has been described by G. L. Bate (1955, Ph.D. thesis, Columbia University).

The samples were introduced into the mass spectrometer as lead tetramethyl, and the isotopic abundances were calculated from the Pb^+ spectrum after the necessary corrections had been made for the monohydride, PbH^+, which is directly observed by the peaks of mass numbers 205 and 209. Spectrographic analyses of the lead chloride demonstrated the absence of Bi^{209} in appreciable concentrations. In order to avoid Hg^{204} at mass 204 an oil-diffusion pump was initially used to provide high vacuum in the tube. However, on prolonged use an increasingly large background signal of organic origin occurred at the mass range of the lead spectrum particularly at mass 207. This background was substantially reduced by replacement of the oil-diffusion pump with a mercury-diffusion pump. The Hg^{204} at mass 204 was corrected for by measuring the Hg^{204}/Hg^{202} ratio before introducing the sample. When the tube was well baked, the mercury background was quite low, and in a typical lead analysis the Hg^{204} contribution to the total mass 204 peak was less than 1 per cent. The measured Hg^{204}/Hg^{202} ratio varied by a few per cent with time and differed by as much as 10 per cent from that reported in the literature. No very accurate evaluation of this ratio could be expected with the small signals involved, and the difference is presumably due to the nonmercury background in mass numbers 202 and 204.

TABLE 2.—DESCRIPTION OF PITCHBLENDE SAMPLES

Sample No.		Locality	Description
Lamont	Robinson		
K-14		Eagle Mine	Pitchblende, massive, unweathered, 200–300 ft. depth
K-24	R-150	Eagle Mine	Pitchblende, massive, unweathered, with traces of galena
K-26	R-420	Eagle Mine	Pitchblende concentrate with hematite, bornite, and chalcopyrite; 1st level
K-25	R-352	Nicholson No. 2 Mine	Pitchblende concentrate with hematite, bornite, and traces of galena; 2nd level
K-28	R-508	Beaverlodge	Pitchblende concentrate with traces of chalcopyrite, clausthalite, and carbonate gangue
K-30	R-352	Pitch-Ore Group	Pitchblende concentrate with clausthalite and chalcopyrite; No. 10 trench at 4-foot depth; slightly weathered
K-31	R-535	Martin Lake Mine	Pitchblende concentrate with some clausthalite, copper selenides, hematite, and calcite
K-32	R-536	Martin Lake Mine	Pitchblende concentrate with hematite and traces of clausthalite(?)
K-33	R-537	Martin Lake Mine	Pitchblende concentrate with hematite, calcite, and traces of clausthalite; slight weathering; near top of No. 1 flow
K-34	R-547	Rix Adit	Pitchblende concentrate with traces of galena and clausthalite(?); unweathered; Leonard series
K-36	R-608	Nesbitt-Labine Mine	Pitchblende concentrate with chalcopyrite and hematite; 2d level; unweathered
K-37	R-609	Nesbitt-Labine Mine	Pitchblende concentrate with chalcopyrite and hematite; 2d level; unweathered
K-38	R-611	American Mines	Pitchblende concentrate; trench GG2
K-42*	R-622	Ace Mine	Pitchblende concentrate with hematite, pyrite, and traces of clausthalite
K-44*	R-625	Ace Mine	Pitchblende concentrate with hematite, pyrite, and traces of clausthalite
K-45*	R-626	Ace Mine	Pitchblende concentrate with hematite, pyrite, and traces of clausthalite
K-48	R-629	Ace Mine	Pitchblende concentrate with hematite, chalcopyrite, and traces of clausthalite; 1st level; east ore body
K-49	R-630	Ace Mine	Pitchblende concentrate; footwall of west ore body; contains hematite with macroscopic clausthalite
K-51	R-632	Ace Mine	Pitchblende concentrate with pyrite, hematite, and traces of clausthalite; east ore body, 2d level
K-53	R-634	Ace Mine	Pitchblende concentrate with pyrite, hematite, and traces of clausthalite; east ore body, 2d level
K-54	R-636	Ace Mine	Pitchblende concentrate with hematite, pyrite, and traces of galena; very slightly weathered; west ore body, 2d level
K-55	R-639	Ace Mine	Pitchblende concentrate with hematite, pyrite, and traces of galena; very slightly weathered; center of west ore body, 2d level
K-50	R-631	Ace Mine	Pitchblende concentrate with hematite, and pyrite; unweathered; located near center of west ore body

* These samples represent a section across the widest part of the west ore body.

However any inaccuracies in the Hg^{204}/Hg^{202} ratio have only a second-order effect in the correction of the Pb^{204} peak for Hg^{204} because of the small amount of mercury involved. In general the larger peaks are reproducible to at least .5 per cent and the 204 peak is reproducible to 1 per cent or more depending on the quantity of Pb^{204}. The procedure and equipment for measuring the radon leakage have been described by Giletti and Kulp (1955). Kulp *et al.* (1954) have described the procedure for analyzing Pb^{210}.

TABLE 3.—DESCRIPTION OF LEAD SAMPLES*

Sample No.		Locality	Description
Lamont	Robinson		
Pb-37	R-653	Ace Mine	Galena; 2d level
Pb-125	R-457	Ace Mine	Clausthalite concentrate
Pb-128	R-642	Beaverlodge Uranium	Clausthalite concentrate; Zone 1 A (trench)
Pb-129	R-643	Reno Group No. 6	Clausthalite concentrate

* All samples contained less than 2 per cent U_3O_8.

SAMPLES

Brief descriptions of the pitchblende samples used in this work are given in Table 2. Very little evidence of weathering was observed in any of the samples except K-19 from the dump of the Nicholson Mine. Some of the raw ore from which the concentrate was produced was used for radon-leakage determinations. Most of these concentrate samples were quartered and other sections were given to the University of Toronto and the United States Geological Survey laboratories. The location of the galena and clausthalite samples are listed in Table 3.

GEOLOGICAL SETTING

The geology of the Lake Athabasca region has been described by Robinson (1950). The area consists of a basement complex of gneisses, schists, and granitic rocks overlain unconformably by the relatively unmetamorphosed Lake Athabasca series consisting of basalts, arkoses, and sandstones. This entire complex is cut by numerous major and minor faults. The pitchblende follows some of these fault systems. It is quite clear, therefore, that the pitchblende was emplaced subsequent to the deposition of the Lake Athabasca series. In the older literature the Lake Athabasca series was considered to be Proterozoic because it is relatively unmetamorphosed. However, the reconnaissance age determinations (Collins *et al.* 1954) indicated that the Lake Athabasca series is at least 1500 m.y. old. Mineralogical studies of the pitchblende by Dr. Robinson have shown a considerable amount of very fine clausthalite which may possibly be of secondary origin. There is evidence for more than one generation of pitchblende, but from the microscopic polished sections alone it is impossible to determine whether this is a second intrusion of pitchblende from depth or simply a local recrystallization due to elevated temperatures.

A study of the geologic map of the Lake Athabasca region shows the pitchblende to be widely distributed in the area. Actually some of the deposits which fall in the same general age range lie in faults outside the Lake Athabasca series, having been deposited in the basement complex. The results which follow demonstrate that the variations in age are not related to any zonal pattern of the district nor do they occur along any particular fault system, but there is excellent evidence that these anomalies persist more or less equally throughout the district. This suggests a regional effect rather than successive deposition along particularly major fracture systems at widely spaced time intervals.

RESULTS

Chemical Analyses

The chemical analyses for lead, uranium, and thorium in this work were provided by the New Brunswick Analytical Laboratory of the

Atomic Energy Commission. The analyses for all of the samples are given in Table 4. To estimate the accuracy and reproducibility, repeat results on three samples by the A. E. C. Laboratory are given in Table 5. The reproducibility is about .2 per cent for uranium and about 1.0 per cent for lead.

Lead Isotopic Data

The raw isotopic data on the lead extracted from the pitchblende is given in Table 6. In almost all cases the concentration of Pb^{204} is so small that the correction for common lead will be minor even if the most contaminated common lead is used for the correction. Table 7 gives the isotopic composition of the lead in the lead minerals which were determined at Lamont. (*Note* the considerable range in composition reflecting the variable contribution from radiogenic lead.)

Summary of Raw Isotopic Ages

Table 8 lists two sets of ages obtained from the isotopic data given in Table 6. In the first set the isotopic composition used for common lead was that of the old uncontaminated galena found in the district, and the other set is obtained by assuming the isotopic composition of clausthalite containing a high concentration of radiogenic lead as the correct composition to use in the common-lead correction. Table 9 gives the corrected per cent of radiogenic lead for each pitchblende sample, assuming the common-lead correction to be based on sample R653 which represents uncontaminated common lead for the district. Table 10 lists the isotopic ages for all samples. The ages are derived from the radiogenic-lead content of Table 9 and the chemical analyses of Table 4. The ages were read off the nomographs prepared by Kulp *et al.* (1954). From Table 10 it is evident that: (1) For a single sample the probable error in age derived from a specific isotopic ratio is small compared to the difference in the ages obtained from the other ratios. (2) These errors are also small compared to the differences between samples. (3) The 206/238 ages are always lower than the 207/235 ages, which in turn are always considerably lower than the 207/206 ages. (4) In no case do all of the ages agree. (5) The isotopic composition of the common lead that is assumed in correcting for common lead does not affect the results. In fact, in most cases it yields a maximum difference of only 1 per cent.

TABLE 4.—CHEMICAL ANALYSES*

Sample No.	Per cent U†	Per cent Th	Per cent Pb
K-14	27.95 ± .04	.005 ± .001	6.43 ± .03
K-24	51.40 ± .02	<.01	11.38 ± .07
K-25	58.74 ± .02	<.01	7.77 ± .03
K-26	52.92 ± .02	.01	7.24 ± .02
K-28	39.90 ± .03	<.01	1.88 ± .03
K-30	18.53 ± .02	.01	3.42 ± .01
K-31	58.44 ± .04	.01	6.86 ± .03
K-33	54.61 ± .07	.025	7.16 ± .03
K-34	65.70 ± .05	.24	7.93 ± .08
K-36	41.04 ± .03	<.01	1.35 ± .02
K-37	40.92 ± .05	<.01	1.95 ± .03
K-38	12.63 ± .03	.017 ± .002	0.52 ± .01
K-42	42.41 ± .02	.08	10.75 ± .08
K-44	16.34 ± .08	.02 ± .01	3.65 ± .04
K-45	34.09 ± .07	.02 ± .01	7.15 ± .06
K-48	37.56 ± .06	.01	1.40 ± .01
K-49	14.56 ± .02	.027 ± .002	2.03 ± .03
K-50	57.66 ± .02	.078 ± .002	15.04 ± .02
K-51	36.33 ± .02	.011 ± .001	3.98 ± .02
K-53	6.93 ± .04	.01	0.25 ± .01
K-54	43.84 ± .01	.11 ± .01	11.38 ± .09
K-55	43.83 ± .06	.07 ± .01	8.26 ± .05

* These analyses were performed by the New Brunswick Analytical Laboratory of the A.E.C. The lead and thorium analyses were done by Dr. W. Bergholz. The uranium analyses were done by Mr. W. Peavy.

† Each analytical value of U, Th, and Pb represents a minimum of two independent determinations.

TABLE 5.—REPRODUCIBILITY OF CHEMICAL ANALYSES

Sample No.	Per cent U	Per cent Th	Per cent Pb
K-24	51.39	<.01	11.29
	51.41	<.01	11.41
	51.44		11.44
K-54	43.84	.11	11.52
	43.83	.10	11.33
	43.86		11.29
K-55	43.89	.07	8.24
	43.77	.07	8.20
			8.34

TABLE 6.—ISOTOPIC DATA OF PITCHBLENDE CONCENTRATES*

Sample No.	204	206	207	208
K-14	<.01	91.2 ± .2	8.61 ± .20	0.18 ± .06
K-24	.015 ± .002	90.5 ± .1	9.02 ± .17	0.49 ± .02
K-25	.02 ± .01	92.1 ± .1	7.49 ± .05	0.35 ± .10
K-26	.014 ± .002	92.5 ± .1	7.20 ± .09	0.30 ± .03
K-28	.021 ± .005	93.0 ± .1	6.26 ± .10	0.718 ± .026
K-30	.168 ± .002	81.9 ± .1	10.91 ± .03	7.03 ± .02
K-31	.011 ± .004	91.4 ± .2	8.11 ± .28	0.59 ± .02
K-33	.025 ± .005	91.9 ± .1	7.37 ± .15	0.70 ± .10
K-34	.038 ± .009	90.8 ± .1	8.03 ± .13	1.15 ± .04
K-36	.07 ± .02	91.5 ± .2	6.70 ± .18	1.73 ± .10
K-37	.052 ± .005	92.6 ± .1	6.08 ± .16	1.28 ± .11
K-38	.11 ± .02	88.4 ± .1	8.08 ± .12	3.41 ± .05
K-42	.024 ± .003	89.6 ± .2	10.00 ± .10	0.35 ± .05
K-44	.050 ± .003	87.8 ± .1	10.50 ± .08	1.71 ± .01
K-45	.021 ± .002	89.6 ± .1	9.82 ± .10	0.60 ± .02
K-48	.023 ± .004	92.6 ± .1	6.45 ± .15	0.96 ± .03
K-49	.08 ± .01	87.6 ± .1	9.62 ± .21	2.72 ± .02
K-50	.012 ± .002	89.8 ± .1	9.81 ± .07	0.47 ± .01
K-51	.03 ± .01	92.2 ± .1	7.03 ± .17	0.82 ± .02
K-53	.23 ± .02	85.0 ± .1	10.08 ± .10	4.70 ± .08
K-54	.017 ± .002	89.4 ± .1	9.91 ± .09	0.69 ± .05
K-55	.012 ± .001	89.9 ± .1	9.70 ± .14	0.44 ± .04

* The data for each sample represent a minimum of two isotopic determinations.

TABLE 7.—ISOTOPIC DATA OF COMMON LEAD IN LEAD MINERALS

Sample No.		204	206	207	208
Lamont	Robinson				
Pb-37	R-653	1.54 ± .01	22.15 ± .04	23.09 ± .06	53.22 ± .06
Pb-125	R-457	1.03 ± .01	41.05 ± .03	19.86 ± .06	38.06 ± .05
Pb-128	R-642	1.23 ± .01	32.66 ± .04	21.19 ± .04	44.65 ± .07
Pb-129	R-643	1.19 ± .01	34.46 ± .07	20.90 ± .05	43.45 ± .08

TABLE 8.—EFFECT OF COMPOSITION OF COMMON LEAD ON ISOTOPIC AGES

Sample No.	206/238	207/235	207/206	
K-54	1550	1630	1795	G*
	1540	1620	1785	R†
K-24	1375	1480	1610	G
	1365	1470	1600	R
K-34	778	920	1300	G
	775	915	1280	R
K-37	325	365	615	G
	320	360	587	R

* G—uncontaminated lead in galena, R-653

† R—highly contaminated lead in clausthalite, R-457

Radon Leakage

Table 11 shows the radon leakage obtained for a representative number of Lake Athabasca samples, and Table 12 compares some of the raw ages given in Table 10 with the ages that would be obtained if the correction for radon leakage is applied. It is immediately observed that the radon-leakage correction is very minor and does not appreciably affect the picture. In some cases even if the 206/238 age is brought into agreement with the 207/235 age by an assumed amount of radon leakage, the 207/206 age is not brought into agreement. It is concluded that radon leakage plays an

insignificant role in explaining the isotopic ages from the Lake Athabasca district.

Pb^{210}

The wide variation in lead 207/206 ages proves that these discrepancies are not due to recent leaching of lead or uranium since such a process would not affect the 207/206 ages. For a check the Pb^{210} concentration may be measured, since this isotope is intermediate in the U^{238}-Pb^{206} decay series. It was of importance to see if the decay series is presently in equilibrium. Figure 1 is a plot of the 206/238 ages versus the 206/210 ages. Within the experimental error these ages fall on a 45° curve for a one to one correlation. The dashed line indicates the curve that would be followed if 10 per cent radon leakage occurred constantly over the life of the mineral. The measured radon leakage in the laboratory amounted to only a few per cent at most. This curve shows that the average radon leakage over the life of the mineral was certainly not greater than about 2 per cent for any of the samples. The large errors in the 206/210 ages are mainly due to the uncertainty in the half-life of Pb^{210}. Evidently all of the samples are presently in radioactive equilibrium.

Possible Alteration Effects

Uranium Loss

The most significant types of alteration of uranium minerals that may occur are loss of uranium, radon, or lead. Each of these alterations will affect the isotopic ratios in a different way.

Experimental work on the solution of uranium minerals is limited. Phair and Levine (1952) have shown that sulfuric acid solutions are capable of dissolving pitchblende under surface conditions. Such conditions would occur only in the vicinity of a sulfide body undergoing rapid oxidation and solution. Even under ordinary weathering conditions, however, secondary uranium minerals are commonplace, which indicate the solution of primary uranium minerals. The early work of Gleditsch and Bakken (1938) showed that during the surface weathering of single crystals of uraninite, the uranium is removed in preference to the lead.

Solution of pitchblende at high temperatures (200°–300°) under reducing conditions has not been established in the laboratory. In fact, recent experiments (L. Miller, 1955, Ph.D. thesis, Columbia) show that under such conditions in the presence of sulfide ions pitchblende is highly insoluble. Table 13 shows the effect of uranium loss on a uranium mineral which was formed at least 10 million years ago. The 206/210 ratio is more sensitive to effects during Recent time than the 207/206 ratio and hence gives additional information on uranium alteration. The number of samples reported in the literature which clearly show evidence of selected removal of uranium are also listed in Table 13. The Crocker's Well and Nicoll's Nob samples were weathered as is clearly seen in hand specimens. Nier mentions specifically that the Huron Claim and Morogoro specimens show alterations. Presumably this was also the case for the Las Vegas monazite.

Table 9.—Corrected per cent of Radiogenic Lead*

Sample No.	206	207
K-14	91.1 ± .2	8.53 ± .20
K-24	90.3 ± .1	8.81 ± .17
K-25	91.9 ± .1	7.34 ± .05
K-26	92.4 ± .1	7.07 ± .10
K-28	92.7 ± .1	5.95 ± .10
K-30	78.8 ± .1	7.85 ± .05
K-31	91.1 ± .2	7.85 ± .28
K-33	91.6 ± .1	7.06 ± .15
K-34	90.3 ± .1	7.53 ± .13
K-36	90.7 ± .2	5.95 ± .20
K-37	92.0 ± .1	5.52 ± .17
K-38	87.0 ± .1	6.58 ± .10
K-42	89.1 ± .2	9.95 ± .10
K-44	87.1 ± .1	9.75 ± .08
K-45	89.3 ± .1	9.56 ± .10
K-48	92.2 ± .1	6.09 ± .17
K-49	86.5 ± .1	8.43 ± .21
K-50	89.7 ± .1	9.60 ± .07
K-51	91.9 ± .1	6.67 ± .17
K-53	83.0 ± .1	8.02 ± .11
K-54	89.1 ± .1	9.61 ± .10
K-55	89.7 ± .1	9.51 ± .14

* The isotopic composition of R-653, an apparently uncontaminated galena from the Ace Creek Mine, was used for the common-lead correction. The correction was based on the Pb^{208} content since there is negligible thorium in the pitchblendes.

TABLE 10.—AGES UNCORRECTED FOR RADON LEAKAGE OR LEACHING EFFECTS

Sample No.	206/238	206/210	207/235	207/206
K-14	1420 ± 10	1440 ± 35	1450 ± 10	1530 ± 20
K-24	1375 ± 10	1345 ± 30	1480 ± 15	1610 ± 40
K-25	860 ± 5	.....	970 ± 10	1220 ± 15
K-26	895 ± 5	890 ± 25	975 ± 10	1140 ± 30
K-28	325 ± 5	340 ± 8	390 ± 15	750 ± 35
K-30	1005 ± 10	955 ± 25	1255 ± 10	1650 ± 20
K-31	765 ± 5	800 ± 20	935 ± 30	1365 ± 10
K-33	852 ± 5	.....	935 ± 10	1140 ± 35
K-34	778 ± 5	755 ± 20	920 ± 15	1300 ± 40
K-36	220 ± 5	.....	285 ± 10	820 ± 60
K-37	325 ± 5	315 ± 8	365 ± 10	615 ± 60
K-38	264 ± 4	.....	375 ± 6	1109 ± 40
K-42	1515 ± 10	.....	1675 ± 10	1840 ± 20
K-44	1315 ± 10	.....	1550 ± 10	1860 ± 20
K-45	1282 ± 10	1280 ± 30	1490 ± 10	1780 ± 20
K-48	254 ± 5	275 ± 8	320 ± 6	820 ± 35
K-49	850 ± 15	860 ± 25	1095 ± 20	1600 ± 40
K-50	1570 ± 10	1560 ± 40	1665 ± 10	1780 ± 20
K-51	714 ± 10	.....	815 ± 20	1065 ± 60
K-53	220 ± 10	.....	395 ± 15	1585 ± 30
K-54	1550 ± 10	1535 ± 45	1630 ± 10	1795 ± 15
K-55	1172 ± 10	1200 ± 30	1400 ± 10	1760 ± 35

TABLE 11.—TYPICAL RADON-LEAKAGE VALUES*

Sample No.	Location	Per cent Leakage
K-14	Eagle Mine	0.064 ± .008
K-30	Pitch Ore Group	2.9 ± .4
K-34	Rix Adit	0.72 ± .05
K-45	Ace Mine	1.90 ± .09
K-48	Ace Mine	2.51 ± .07
K-54	Ace Mine	4.3 ± .4
K-55	Ace Mine	0.26 ± .03

* Values determined at room temperature

Since this type of alteration may be readily observed in hand specimens, careful sample selection should make it possible to eliminate anomalies of this nature.

Radon Leakage

Generally radon leakage has a range of .01–1.0 per cent for samarskite, .5–5 per cent for uraninite, .1–10 per cent for pitchblendes, and 10–30 per cent for secondary uranium minerals such as carnotite (Giletti and Kulp, 1955).

Table 14 lists the effect of radon leakage on the ages obtained from the various isotopic ratios. Laboratory measurement of radon leakage can be readily carried out as a function of temperature. In general the rate increases by a factor of 2–4 up to 200° C, above which

TABLE 12.—RADON-LEAKAGE CORRECTIONS ON ISOTOPIC AGES OF SOME REPRESENTATIVE LAKE ATHABASCA SAMPLES

Sample No.	Per cent leakage at room temp.	206/238	207/235	207/206	
K-30	2.9 ± .4	1005	1225	1650	U
		1034	1225	1602	C
K-34	.72 ± .05	778	920	1300	U
		784	920	1291	C
K-45	1.90 ± .09	1282	1490	1780	U
		1307	1490	1745	C
K-48	2.51 ± .07	254	321	820	U
		260	321	760	C
K-54	4.3 ± .4	1550	1630	1795	U
		1615	1630	1710	C
K-55	.26 ± .03	1172	1400	1760	U
		1175	1400	1755	C

U = Uncorrected for radon leakage

C = Ages corrected for the leakage of radon according to the room temperature rate

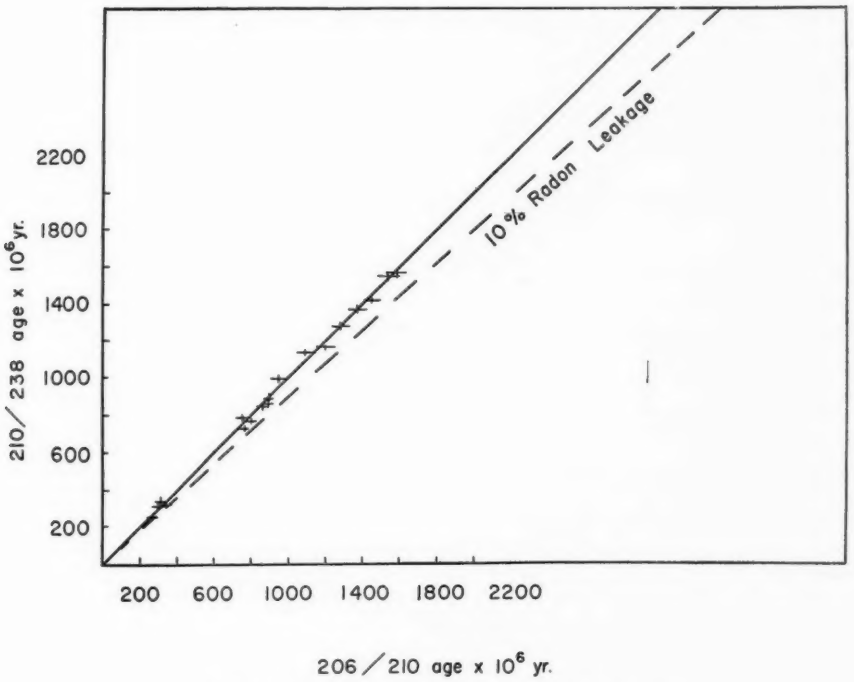


FIGURE 1.—COMPARISON OF 206/238 AND 206/210 AGES

TABLE 13.—EFFECT OF URANIUM LOSS ON VARIOUS ISOTOPIC AGES*

Time of uranium loss	Age			
	206/238	207/206	207/235	206/210
Yesterday	too old	correct	too old	correct
10,000 years ago	too old	correct	too old	correct
1×10^8 years ago	too old	essentially correct	too old	same as 206/238

Locality	Laboratory	206/238	207/206	207/235
Huron claim (monazite)	Nier	3180	2610	2840
Las Vegas (monazite)	Nier	1723	1300	1547
Morogoro (uraninite)	Nier	790	612	743
Crockers Well (brannerite)	Lamont	545	470 ± 40	535
Nicoll's Nob (pitchblende)	Lamont	445	340 ± 65	430

* For all fractions of uranium removed and for all times 206/238 age > 207/235 age > 207/206 age.

it appears to decrease owing to recrystallization. The pressure effect in the crust of the earth should decrease the radon leakage by closing fissures and decreasing both porosity and permeability. Throughout most of their history primary uranium minerals probably leak less radon than is measured in the laboratory. Since the Lake Athabasca samples show a radon leakage of 0.2–4 per cent in the laboratory, and since these samples are relatively

old, the radon-leakage correction must be small.

Lead Loss

The effect of lead loss on the various isotopic ages by exsolution from recrystallization difference between the 207/206 age and the 207/235 age. The wide variation in the 207/206 ages in the pitchblendes of the Lake Athabasca region (Table 10) shows that the important lead loss did not occur in the last million years. This is consistent with the previous observa-

TABLE 14.—EFFECT OF RADON LEAKAGE ON VARIOUS ISOTOPIC AGES

Radon Leakage	Age			
	206/238	206/210	207/235	207/206
Appreciable in last 100 years —none earlier	correct	too old	correct	correct
Constant during life of minerals	too young	correct	correct	too old; strong effect on young minerals; effect equals that on 206/238 for mineral > 1.0 b.y.
Average leakage during history ≫ last 100 years	too young	equals 206/238	correct	too old
Average leakage during history ≪ last 100 years	slightly too young	too old	correct	slightly too old
Average leakage < 2%	correct to 2%	equals 206/210 unless lab. leakage high	correct	correct to 5% if > 1500; correct to 10% if > 500

TABLE 15.—EFFECT OF LEAD LOSS ON VARIOUS ISOTOPIC AGES OF URANIUM MINERALS AT LEAST 10 MILLION YEARS OLD

Lead loss	Age			
	206/238	206/210	207/235	207/206
Now	too young	correct	too young	correct
100 years ago	too young	equal 206/238	too young	correct
1×10^8	too young	equal 206/238	too young	essentially correct

For all fractions of lead removed and for all times

$$207/206 > 207/235 > 206/238$$

of uranium minerals that are at least 10 million years old is shown in Table 15. The order of the apparent ages obtained from the three isotopic ratios for all fractions of lead removed and for all times is the same as that obtained for radon leakage, but as indicated earlier, the actual radon leakage is not large enough to explain the difference. About 70 per cent of all the uranium minerals that have been analyzed show this sequence of apparent ages. All of the Athabasca samples show this effect. For a very old mineral, the greater the fraction of lead removed in its recent history, the greater the tion that surface weathering normally results in uranium loss rather than lead loss.

The process of lead loss from a uranium mineral is expected on thermodynamic grounds since the lattice is greatly strained by the insertion of the larger divalent Pb^{++} (1.32°A) ion for the tetravalent U^{+4} (1.05° A). The fact that many uranium minerals, even some very old ones, *e.g.* the Ebonite Claims, Bikita, So. Rhodesia monazite 2650 m.y. (Holmes, 1954) and Wilberforce uraninite, 1030 m.y. (Nier, 1939), give concurrent ages proves that appreciable lead loss does not always occur and

is certainly not a continuous process. The rate of lead exsolution, at least, under surface conditions appears entirely too small to show an effect on the ages.

Little experimental work has been done to define the conditions under which lead can be removed from uranium minerals. Some preliminary experiments done by Føyn (1938) show that lead can be removed at elevated temperatures. Seven g of carefully separated black uraninite (var. bröggerite) were placed in a steel bomb with distilled water at 190°C for 20 hours; after cooling the sample exhibited no noticeable alteration.

The same procedure was repeated at a temperature of 290°C for 10 hours. Examination of the product revealed the presence of a red coating on the uraninite. The red secondary product was removed by scraping and was analyzed for the various constituents. The results are given in Table 16.

TABLE 16.—EXSOLUTION OF LEAD FROM URANINITE AT 290°C

Element	Primary mineral	Secondary product (weight = 0.01284 g.)	H_2O
PbO	9.63	30.1%	trace
Fe_2O_3	0.36	71.5	trace
U_3O_8	76.20	trace	trace
ThO_2	7.82	trace	.....
Ra	2.22×10^{-7}g/g	5×10^{-12}g	5×10^{-12}g

The data show that the secondary product has a much higher per cent concentration of lead oxide than the primary mineral, while the water contains only trace amounts. In contrast to this the uranium concentration in the secondary product was negligible compared to a concentration of 7.82 per cent in the primary material. Thus radiogenic lead had been exsolved.

It is concluded that lead can be removed from pitchblende and uraninite during an increase in the regional temperature. The temperature need not have exceeded 300°C. The extent of lead loss would presumably depend on the water concentration in the environment and the time interval during which the temperature was elevated. Further experimental work on this problem is planned at Lamont.

DISCUSSION

Analysis of Common-Lead Data

Table 17 is a compilation of isotopic data from several samples of galena and clausthalite concentrates from the Lake Athabasca district. R653 was chosen because it most probably represents common lead emplaced at about the same time as the initial pitchblende deposition. This sample of galena from the Ace Creek Mine shows no evidence of contamination by radiogenic lead since the time of deposition and was taken from a quartz-vein system which contained no radioactive minerals. The other six samples were selected because they carried high concentrations of radiogenic lead. In no case was the uranium content of these concentrates sufficient to have contributed appreciable radiogenic lead since the time of their formation.

In addition to R653, the theoretical isotopic composition of average continental rock lead at 200 m.y. and 1000 m.y. ago is given based on the curves of Bate (1955, Ph.D. thesis, Columbia).

Now consider the following process: At some time after the initial deposition of the pitchblende at Lake Athabasca the region was heated up. Under this condition lead may be mobilized from the following sources: old common-lead minerals, primarily galena, radiogenic lead from the pitchblende, and rock lead from the Lake Athabasca series and the Tazin formation. From the isotopic data of Table 17, it is possible to determine two important facts. The time of lead loss can be ascertained from the 207/206 ratio of the radiogenic fraction of the clausthalite or galena provided that the time of initial deposition of the pitchblende is

known. Further, the relative contribution of the three sources of the lead may be calculated.

Since the thorium content of the pitchblendes is negligible, the 208/204 ratio in these leads less than 2.1 b.y. If the initial pitchblende deposition occurred at 1.9 b.y., the 207/206 ratios obtained from these clausthalite and galena concentrates suggest periods of recrystal-

TABLE 17.—ISOTOPIC ANALYSIS OF LEAD FROM CLAUSTHALITE AND GALENA CONCENTRATES, LAKE ATHABASCA DISTRICT

Sample	204	206	207	208	Probable composition of lead			(207/206)
					Per cent Pitch-blende	Per cent Old common	Per cent Younger rock	
R-653 (Ace galena)	1.00	14.36	14.96	34.49	0	100	0	.....
Rock lead ∽ 200 m.y.age	1.00	18.1	15.7	38.2	0	0	100	.....
Rock lead ∽ 1000 m.y.age	1.00	17.5	15.6	37.4	0	0	100	.....
R-457	1.00	40.01	19.36	37.10	27	7	66	.17 ± .01
	‡(1.00	17.2	15.5	37.1)				
R-642	1.00	26.55	17.26	36.48	11	21	67	.18 ± .015
	(1.00	16.3	15.3	36.5)				
R-643	1.00	28.96	17.56	36.51	15	21	64	.17 ± .015
	(1.00	16.3	15.3	36.5)				
*R-313	1.00	58.1	21.9	37.7 ± .4	47	0	53	.16 ± .01
	(1.00	17.5	15.6	37.4)				
†R-3	1.00	43.5	18.7	35.7	31	47	22	.12 ± .01
	(1.00	15.6	15.3	35.7)				
*R-259	1.00	29.1	17.0	38.5	12	0	88	.12 ± .02
	(1.00	18.1	15.7	38.5)				

* Permission to quote kindly granted by R. M. Farquhar and R. D. Russell, University of Toronto

† Collins *et al.* (1954)

‡ Parentheses indicate probable isotopic composition of lead in clausthalite and galena derived from rock lead plus old common lead.

may be used to derive a probable isotopic composition of the nonradiogenic lead (*i.e.*, the rock lead plus old common lead) in the sample of clausthalite or galena. The Pb^{206} and Pb^{207} concentration of nonradiogenic lead may now be subtracted from the total. The result is the quantity of Pb^{206} and Pb^{207} derived from the pitchblende at the time the lead was exsolved, and hence, the percentage of radiogenic lead in the sulfide and selenide. Column six of Table 17, shows that the exsolved lead appears to have two distinct 207/206 ratios, *i.e.*, 0.17 ± .01 and 0.12 ± .01. Figure 2 shows the change in the ratio of 207/206 with time for a pitchblende which was deposited 2.1 or 1.9 b.y. ago. The fact that the 2.1 curve intersects the ordinate at 207/206 = .13 suggests that the time of pitchblende deposition must have been

lization and lead exsolution around 1.2 b.y. and 0.15 b.y. ago.

In order to distinguish the rock-lead component from the old common-lead component, it is necessary to estimate the time of formation of the clausthalite or galena from the radiogenic 207/206 ratio. Then a comparison of the Pb^{208}/Pb^{204} ratio actually present and a knowledge of this ratio in rock lead for that particular time permit an estimate of the fraction of the total lead contributed from these two sources. Thus R313 had no old common lead whereas R3 had about 50 per cent. The estimate of the fraction of the total lead derived from the pitchblende in these minerals is much more precise than that for the other two sources.

Measurement of the isotopic composition of the many additional samples of clausthalite

and galena might make it possible to prove whether there were more than two periods of lead removal. The major difficulty with this method of defining the times of lead loss is the large error that must be assigned to the radiogenic 207/206 ratio. Only in samples containing at least 20 per cent radiogenic lead does the error in the ratio reduce to ±.01.

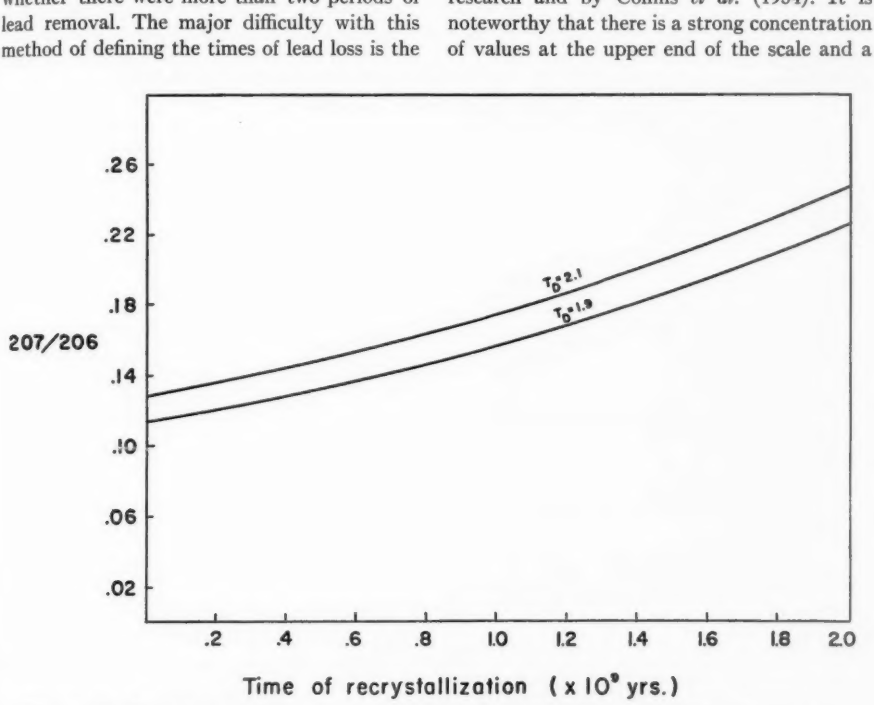


FIGURE 2.—EFFECT OF RECRYSTALLIZATION ON THE 207/206 RATIO FOR TWO PERIODS OF DEPOSITION

Apparent Age of Pitchblende from Uncorrected Isotopic Ratios

Ages obtained for all samples of pitchblende concentrate from the three isotopic ratios are given in Table 10. The general pattern of ages is that which would be expected for variable amounts of lead exsolved after the initial deposition of pitchblende. If there were no lead exsolution but only several periods of primary uranium mineralization, the ages for at least some of the individual samples would be concurrent and thus indicative of the times of deposition. No such relationship is observed in the data. The 207/206 ages range from 615 to 1860 m.y. Figure 3 is a histogram showing all the 207/206 ages reported both by this research and by Collins *et al.* (1954). It is noteworthy that there is a strong concentration of values at the upper end of the scale and a cutoff at about 600 m.y. on the lower end. This suggests that the initial deposition occurred only slightly more than 1860 m.y. ago and that the final recrystallization occurred less than 600 m.y. ago.

The 206/238 age of 220 m.y. obtained for K-36 and K-53 shows that the last period of recrystallization actually occurred less than 220 m.y. ago.

K-53 is a particularly significant sample since it has a very high 207/206 age of 1585 m.y. accompanying the 206/238 age of only 220 m.y. This array of ages severely restricts the time of initial deposition. It is certain the lead removal did not occur during the past million years because of the discrepancies in the 207/206 ages. The dominant period of lead removal for K-53 must have been less than 220 m.y. ago. A calculated initial time of 1900 m.y. ago is required for the three ages for K-53 to be explained by removal of 92 per cent of the lead

80 m.y. ago. If the lead removal occurred between 80 m.y. and 1 m.y. ago the difference in the required time of deposition is negligible. If the recrystallization occurred prior to 200 m.y. ago the ages cannot be brought into line unless the time of initial deposition is less than 1860 m.y. which is impossible. It is concluded that the initial deposition occurred 1900 ± 20 m.y. ago.

If all the samples treated in this manner showed a narrow range for the time of recrystallization, it would be strong evidence that there was only one such period. Actually the apparent times range from 80 m.y. to 1200 m.y., although there is a cluster of times below 400 m.y. indicating a dominant period of recrystallization subsequent to 400 m.y. ago. Hence, there are at least three strong arguments against a single period of recrystallization: (1) the lack of agreement in the apparent time of recrystallization among the samples; (2) there are several samples which cannot be made concurrent no matter what time or fraction of lead loss is assumed; and (3) the common-lead data.

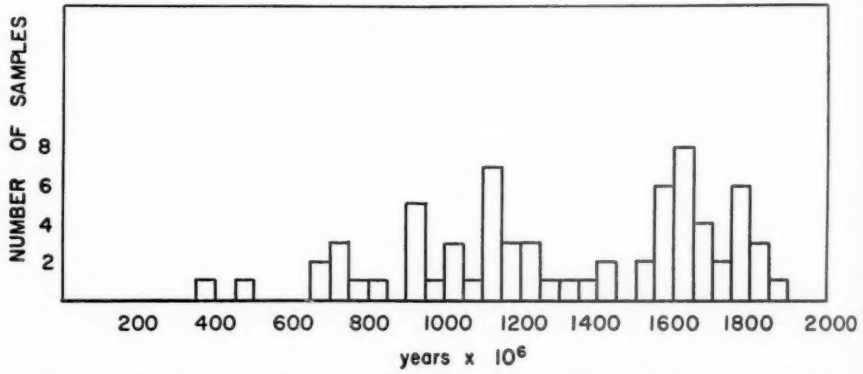


FIGURE 3.—HISTOGRAM OF REPORTED 207/206 AGES FROM THE LAKE ATHABASCA REGION

Possible Interpretations

If the indication of two periods of lead removal from the clausthalite and galena data is ignored, the simplest interpretation of the anomalous ages would be that the initial deposition occurred at 1900 m.y. ago and that this was followed by a single period of lead loss. Making this assumption, families of curves were drawn for each of the isotopic ratios. The fraction of lead lost was plotted against the apparent age for various times of recrystallization. By the use of these curves it was possible to derive unique quantities for the fraction of lead lost if there were only one period of recrystallization and the time of such a recrystallization were known. In the case of samples K-50 and K-54 no set of conditions is adequate to explain the data if only one period of recrystallization is permitted. These data are summarized in Table 18. In other words if the isotopic ratios are corrected for the particular fraction of lead lost at the time shown in Table 18, the age from all three isotopic ratios would be 1.9 b.y.

If two periods of recrystallization are assumed, one about 1200 m.y. ago and the other from 100 to 150 m.y., then the ages from the three isotopic ratios for all samples can be corrected to 1900 m.y. for specific fractions of lead lost at each period of recrystallization. It can be shown mathematically that any larger number of periods of recrystallization could also account for the ages in Table 10.

It may be concluded that the time of initial pitchblende deposition in the Lake Athabasca district occurred at 1900 ± 40 m.y. The pitchblende was subjected to at least two periods of recrystallization, one between 100 and 200 m.y. and the other about 1200 m.y. ago. This hypothesis accounts for all of the isotopic data from the common-lead minerals as well as the data from the pitchblende samples. These conclusions are also in agreement with the mineralogical and geological data.

Geological Significance

The results suggest that the basement complex in the Lake Athabasca region is older than previously inferred by Collins *et al.* (1954). Since the initial pitchblende deposition which occurred 1900 m.y. ago cuts the unmetamorphosed Lake Athabasca series and this in turn lies unconformably on the basement complex (Tazin series), the latter must be at least 2200 m.y. old. Several unpublished dates on uranium minerals from pegmatites in this region (R. J. Traill, personal communication) are not concordant, but the 207/206 age exceeds 2100 m.y. Since these minerals must have been subject to the same thermal rise that affected the pitchblende in the same district, it is certain that the true time of pegmatite intrusion exceeds 2200 and may be 2300 m.y. or more.

These results are important not only because they show that rocks may exist for two billion years without being metamorphosed but also because the age of this important part of the Canadian Shield has been increased by about 700 m.y. Further, the presence of anomalous ages due to lead loss indicates that at least one period of increase in the regional temperature occurred subsequent to the deposition of the uranium minerals. For certain metamorphic provinces this may be valuable information. Conversely, concurrent ages from the different isotopic ratios prove the absence of any such event after deposition of pitchblende.

TABLE 18.—TIME AND FRACTION OF LEAD REMOVAL

Sample No.	206/238	207/235	207/206	Time of removal $\times 10^9$ yr.	Fraction of lead removed
K-14	1420 ± 10	1450 ± 10	1530 ± 20	1.15 ± .05	.64
K-24	1375 ± 10	1480 ± 15	1610 ± 40	.80 ± .05	.51
K-25	860 ± 5	970 ± 10	1220 ± 15	.65 ± .05	.84
K-26	895 ± 5	975 ± 10	1140 ± 30	.76 ± .05	.89
K-28	325 ± 5	390 ± 15	750 ± 35	.30 ± .03	.97
K-30	1005 ± 10	1255 ± 10	1650 ± 20	.33 ± .05	.61
K-31	765 ± 5	937 ± 30	1365 ± 10	.45 ± .05	.80
K-33	852 ± 5	937 ± 10	1140 ± 35	.7 ± .1	.89
K-34	778 ± 5	920 ± 15	1300 ± 40	.55 ± .05	.85
K-36	220 ± 5	285 ± 10	820 ± 60	.16 ± .02	.97
K-37	325 ± 5	365 ± 10	615 ± 60	.30 ± .02	.98
K-38	264 ± 4	373 ± 6	1109 ± 40	.16 ± .02	.94
K-42	1515 ± 10	1675 ± 10	1840 ± 20	.30 ± .06	.26
K-44	1315 ± 10	1550 ± 10	1860 ± 20	.16 ± .04	.36
K-45	1282 ± 10	1490 ± 10	1780 ± 20	.32 ± .05	.42
K-48	254 ± 5	321 ± 6	820 ± 35	.15 ± .02	.96
K-49	850 ± 15	1095 ± 20	1600 ± 40	.35 ± .03	.70
K-50	1570 ± 10	1663 ± 10	1780 ± 20	.....	.....
K-51	714 ± 10	815 ± 20	1067 ± 60	.55 ± .05	.90
K-53	220 ± 10	395 ± 15	1585 ± 30	.08 ± .02	.92
K-54	1550 ± 10	1630 ± 10	1795 ± 15	.....	.....
K-55	1172 ± 10	1400 ± 10	1760 ± 35	.30 ± .05	.49

Geochronological Significance

This study of the Lake Athabasca district graphically illustrates that lead removal occurs in uranium minerals under suitable conditions. This general principle can explain most of the anomalous ages. In most other localities only a single sample has been studied, from which only limited information regarding the true age can be derived. If the ages are concordant the age may be accepted with confidence. If not, the 207/206 age is simply a minimum one although the extent of the discrepancy may be useful in determining the approximate age. That such an estimate must be considered tentative is seen by a comparison of K-30 and

K-37 in Table 10. In these cases the discrepancies are similar, but the apparent 207/206 ages are highly divergent.

One of the most important contributions to geochronometry that has resulted from this study is the concept that it is necessary to make complete isotopic and chemical measurements on more than one sample from a locality. Conversely, a complete study involving a large number of specimens permits considerable information to be derived concerning the geologic history.

Several papers on the geology of the Canadian Shield have been based on 207/206 ages alone (Wilson, 1949). Although the broad theories propounded in these papers may not be changed by the required upward revision of the ages of certain localities, the "fine structure" probably will be affected.

One of the currently important problems in geochronometry is the calibration of the Rb-Sr and K-A methods of age determination. This has been attempted by comparing the results obtained from these radioactive decay schemes with the uranium-lead clock. Great care must be taken in selecting uranium-lead dates for comparison, particularly since many of the comparisons have been made using only 207/206 ages.

Conclusions

(1) The process of lead exsolution from uranium minerals occurred at least twice in the Lake Athabasca district.

(2) The initial deposition of the pitchblende occurred close to 1900 m.y. ago and recrystallizations accompanied by lead removal probably occurred about 1200 m.y. and 100–200 m.y. ago. This was probably due to a mild regional metamorphism. Other periods of lead exsolution may have occurred but explicit evidence is lacking.

(3) The process is a general one and explains most of the anomalous uranium-lead ages.

(4) Agreement among the isotopic ages from a given locality is excellent evidence that the true absolute age is known. Further, it is proof that the area has not been subjected to appreciable thermal rise since the time of formation of the mineral. Conversely, anomalous ages of the type obtained for lead loss prove the occurrence of one or more periods in which the regional temperature has increased.

(5) Early Precambrian uranium minerals cannot be dated with confidence merely from a 207/206 measurement. The 207/206 age is a minimum and in extreme cases may be low by a factor of one-half.

(6) Complete isotopic analyses on a number of specimens from a locality are desirable if a close approximation of the true age is desired.

Further papers in this series will report new measurements and will re-evaluate the age of each locality in terms of the processes defined in this study.

References Cited

Collins, C. B., and Freeman, J. R., 1951, Geological age determinations in the Canadian Shield: Royal Soc. Canada Trans., v. 16, p. 23–30.

Collins, C. B., Farquhar, R. M., and Russell, R. D., 1954, Isotopic constitution of radiogenic leads and the measurement of geological time: Geol. Soc. America Bull., v. 65, p. 1–21.

Collins, C. B., Lang, A. H., Robinson, S. C., and Farquhar, R. M., 1952, Age determinations for some uranium deposits in the Canadian Shield: Geol. Assoc. Canada Proc., v. 63, p. 15–41.

Føyn, E., 1938, Die verwitterung der uranmineralien: Norsk geologisk tidsskrift, v. 17, p. 197–202.

Giletti, B. J., and Kulp, J. L., 1955, Radon leakage from radioactive minerals: Am. Mineralogist, v. 40, p. 481–496.

Gleditsch, E., and Bakken, R., 1937, The determination of UO_2 and UO_3 in different layers of a single crystal of uraninite: Mikrochim. Acta, v. 1, p. 83–86.

Holmes, A., 1947, The construction of a geological time-scale: Geol. Soc. Glasgow Trans., v. 21, p. 117–152.

——1954, The oldest dated minerals of the Rhodesian Shield: Nature, v. 173, p. 612–614.

Kerr, P. F., and Kulp, J. L., 1952, Pre-Cambrian uraninite, Sunshine Mine, Idaho: Science, v. 115, p. 86–88.

Kulp, J. L., Bate, G. L., and Broecker, W. S., 1954, Present status of the lead method of age determination: Am. Jour. Sci., v. 252, p. 345–364.

Kulp, J. L., Broecker, W. S., and Eckelmann, W. R., 1954, Age determination of uranium minerals by the Pb^{210} Method: Nucleonics, v. 11, p. 19–21.

National Research Council, 1949, Report of the Committee on the Measurement of Geologic Time for 1947–1948, p. 16–18.

Nier, A. O., 1939, The isotopic constitution of radiogenic leads and the measurement of geological time. II: Phys. Rev., v. 55, p. 153–163.

Nier, A. O., Thompson, R. W., and Murphy, B. F., 1941, The isotopic constitution of lead and the measurement of geological time. III: Phys. Rev., v. 60, p. 112–116.

Phair, G. and Levine, H., 1952, Notes on the differential leaching of uranium, radium, and lead from pitchblende in H_2SO_4 solutions: U. S. Geol. Survey Prelim. Rept.

Robinson, S. C., 1950, Mineralogy of the Goldfields District, Saskatchewan: Geol. Survey Canada Paper 50-16.

Stieff, L. R., Stern, T. W., and Milkey, R. G., 1953, A preliminary determination of the age of some Colorado Plateau uranium ores by the uranium-lead method: U. S. Geol. Survey Trace Elements Inv. Rep. 268.

Wilson, J. T., 1949, Some major structures of the Canadian Shield: Canad. Min. Metall. Bull., v. 42, p. 231–242.

LAMONT GEOLOGICAL OBSERVATORY (COLUMBIA UNIVERSITY), PALISADES, N. Y. Contribution No. 170.

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, FEBRUARY 10, 1955.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 67, PP. 55–106, 8 FIGS., 2 PLS. JANUARY 1956

ORDOVICIAN LIMESTONES IN THE WESTERN ANTICLINES OF THE APPALACHIANS IN WEST VIRGINIA AND VIRGINIA NORTHEAST OF THE NEW RIVER

BY MARSHALL KAY

ABSTRACT

Middle Ordovician limestones of the Chazyan, Bolarian, and Trentonian series are exposed in the western anticlines in the Appalacian Mountains of West Virginia and in Virginia northeast of the New River. The term Western Anticlines is applied to those cove-breeched structures which contrast with the dominantly homoclinal, fault-bounded slices west of the New River.

The Chazyan comprises the Lurich and Lincolnshire formations. The Lurich has a persisting calcilutite, the Five Oaks, at its top; in the southwest it has a middle member, the Elway, a cherty limestone, overlying a lower, Blackford, member containing chert-pebble conglomerate. The Lincolnshire limestone has disconformities above and below, thins to local extinction, and is overlapped by younger beds northward in Pennsylvania.

The Bolarian rocks are in two groups. The lower has three limestone formations, Ward Cove, Peery, and Benbolt; the Peery persists as a cherty datum. The Ward Cove varies in lithic sequence and thins toward the northwest, probably by overlap and convergence. The Benbolt also has changing facies but is of more constant thickness. The upper Bolarian is of two newly named units, McGlone and McGraw limestones; the latter is particularly distinctive and disappears southeastward, probably beneath a regional unconformity.

Trentonian rocks lie with disconformity on the Bolarian. In the southwest the lower Trentonian is dominantly Moccasin reddish argillite; northeastward it changes into fossiliferous Nealmont limestone of a facies like that in Pennsylvania. In the southwest the Eggleston argillaceous shale has a basal quartz sandstone, and in the northwest it passes into the Onego argillaceous limestone which resembles the Oranda limestone of the Appalachian Valley. Volcanic ash beds persist in all three. The younger Trentonian has not been successfully divided and traced and is called the "Martinsburg," though in the northeastern exposures it is essentially like the Salona limestone of Pennsylvania.

An erosion surface of low relief bevelled the lower Ordovician carbonate rocks. The Chazyan Lurich carbonate rocks blanketed the Western Anticlines and areas to the southeast, and the Lincolnshire covered most of the outcrop area in the Virginias. Differential deformation increased in Bolarian, for lower units thicken southeastward and become argillaceous and quartz-arenaceous. During late Bolarian there was gentle northwest tilting. In the south sources to the southeast were rejuvenated in early Trentonian, producing reddish clays and silts that filled the margins of an adjoining trench. In later Trentonian diastrophism was moderate, but calcareous facies in the Western Anticlines grade southeastward into argillaceous sediments.

Structural trends are similar to those in Pennsylvania and New York, although the tectonic events that most strongly influenced sedimentation were not synchronous along the whole Appalachian belt. Stable periods were interrupted by deformation of belts to the southeast.

CONTENTS

TEXT

	Page
Introduction	56
Acknowledgments	58
Reference section	58
Regional subdivision	59
Chazyan Series	69
Lurich formation	69
Lincolnshire limestone	72
Bolarian Series	77

	Page
General statement	77
Ward Cove limestone	78
Peery limestone	81
Benbolt limestone	81
Hatter formation	82
McGlone limestone	82
McGraw limestone	83
Trentonian Series	84
Correlation	84
Moccasin and Eggleston formations	84
Nealmont and Salona formations	87
Edinburgh, Oranda, and Martinsburg formations	91
Classification and correlation	94
Paleogeography and tectonics	99
References cited	104

ILLUSTRATIONS

Figure	Page
1. Outline map	57
2. Sections of Lurich formation	59
3. Sections of Bolarian formations and Lincolnshire	76
4. Restored section of Bolarian formations	80
5. Sections of Trentonian in Western Anticlines	86
6. Resoted section of lower Trentonian rocks	88
7. Sections of Trentonian in Appalachian Valley	90
8. Correlation table	95

Plate	Facing page
1. Appalachian anticline and Ordovician limestone	56
2. Bolarian and Trentonian formations	57

TABLES

Table	Page
1. Section near Narrows, Virginia	60
2. Section near Gap Mills, West Virginia	62
3. Section in Snake Run Cove, Virginia	64
4. Section in eastern Richpatch Cove, Virginia	65
5. Section in southern Warm Spring Cove, Virginia	66
6. Section west of Healing Spring, Virginia	67
7. Section near Bolar, Virginia	68
8. Section in southern Bluegrass Cove, Virginia	69
9. Section near Trimble in northern Bolar Cove, Virginia	70
10. Section near Bluegrass, Virginia	71
11. Section near Harpers Gap, West Virginia	73
12. Section northwest of Loysburg, Pennsylvania	74
13. Section between Green Mount and Antioch churches, Rockingham County, Virginia	91
14. Faunules from the Onego member, Salona formation	92
15. Faunules from Oranda and Martinsburg formations	93
16. Glossary of names of middle Ordovician stratigraphic units	102

Introduction

The region has three limits, represented by sections in Pendleton County, West Virginia, on the north, at The Narrows of the New River on the southwest, and at Richpatch Cove, Virginia, on the southeast (Fig. 1). The stratigraphy was discussed in a brief summary published by the writer in 1948, and in more detail by Woodward in 1951. Although the two do not reach identical conclusions, the differences are slight, particularly when compared to preceding articles. The writer published maps showing thicknesses of several units (Kay, 1948); these have not been reprinted in the present paper.

Correlation with adjacent rock units and classification against the standard section in New York (Fig. 8) are more uncertain. To the north, Central Pennsylvania (Kay, 1943) is directly along the facies trends. On the east investigations in a different province, the Appalachian Valley, have extended from Virginia (Cooper and Cooper, 1946) to southern Pennsylvania (Craig, 1949; Newman, 1951); the present paper concerns exposures nearest the Western Anticlines. On the southwest there is continuity into areas studied by B. N. Cooper and C. E. Prouty (1943; Cooper, 1944; 1951; Prouty, 1946).

General sections toward the limits of the area will be described first, then the continuity of the principal stratigraphic units within the region, and finally the correlation and classifi-

PLATE 1.—APPALACHIAN ANTICLINE AND ORDOVICIAN LIMESTONES

FIGURE 1.—BOLAR COVE, HIGHLAND AND BATH COUNTIES, VIRGINIA
View south from Sounding Knob showing Ordovician surrounded by Silurian quartzite ridges

FIGURE 2.—CHAZYAN LINCOLNSHIRE LIMESTONE
Upper reef zone in southeast Warm Springs Cove, Alleghany County, Virginia

FIGURE 1

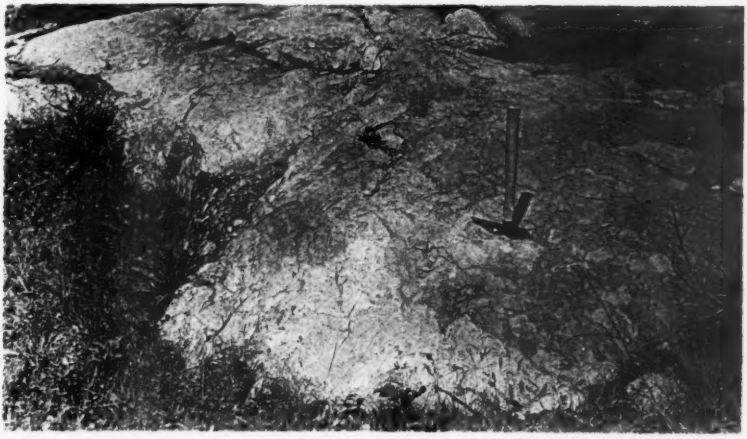


FIGURE 2

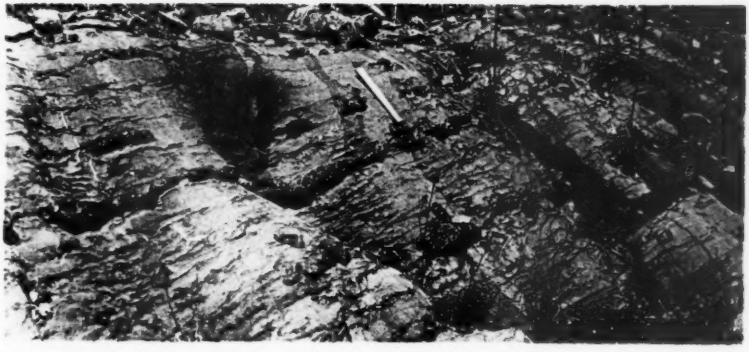


FIGURE 3

APPALACHIAN ANTICLINE AND ORDOVICIAN LIMESTONE

FIGURE 1

FIGURE 2

FIGURE 4

FIGURE 3

BOLARIAN AND TRENTONIAN FORMATIONS

cation. The formations are commonly fossiliferous, and many fossils have been collected. The faunas are being studied by several paleontologists. G. A. Cooper is preparing a monograph on the brachiopods. B. N. Cooper (1953) and Whittington and Evitt (1953) have studied trilobites from areas to the east and south. The fossil distribution seems in accord with conclusions based on lithic studies.

The sections studied are along the flanks of the Western Anticlines of the Appalachian Mountains and adjoin the Allegheny Front and the gently dipping rocks of the Plateau (Fig. 1). On the northwest flanks of the anticlines the dip increases to vertical or slightly overturned; on the southeast it is more gentle. The northernmost extensive exposure of middle Ordovician rocks is in northeast-trending Germany "Valley" or Cove northwest of Franklin, in Pendleton County, West Virginia. South-

FIGURE 1.—OUTLINE MAP
Showing Localities in Western Anticlines of the Appalachian Mountains and to the North.

PLATE 2.—BOLARIAN AND TRENTONIAN FORMATIONS

FIGURE 1.—BASAL MOCCASIN LIMESTONE OVERLYING MCGRAW "CAMAROCLADIA" BEDS
Near Scales, Tazewell County, Virginia

FIGURE 2.—BASAL MOCCASIN LIMESTONE OVERLYING MCGRAW LIMESTONE
Along Virginian Railway north of Narrows, Giles County, Virginia

FIGURE 3.—NEALMONT LIMESTONE ON *Camarocladia*-BEARING STOVER LIMESTONE
East end of quarry north of Highway 869, north of Loysburg, Bedford County, Pennsylvania

FIGURE 4.—BASAL CHAUMONT LIMESTONE DIRECTLY ABOVE THE LOWVILLE
Camarocladia-bearing beds in quarry by railroad bridge in Lowville, Lewis County, New York

westward, the axis of the cove passes into the western part of the structurally more complex Bluegrass Cove of Highland County, Virginia, isolated by the younger Ordovician outcrop around Snowy Mountain at the State line. To the east, en echelon, is the "Big Valley" or or Bolar Cove, extending southwestward from Sounding Knob in Highland County to beyond Bolar on the Bath County line. The nearest middle Ordovician outcrop in Warm Springs Cove is 15 miles southwestward nearly in the same southwest trend; interrupted exposures continue along Warm Springs Cove for another 15 miles southwestward into northern Alleghany County near Falling Spring.

Snake Run Cove, at the eastern end of St. Clair fault, lies about 20 miles southwest of Warm Springs Cove near Sweet Chalybeate, Virginia, and Sweet Springs, West Virginia. To the southeast, middle Ordovician crops out for about 10 miles along the double anticlinal structure of southwest-trending Richpatch Cove, in which the southwestern exposures are about 10 miles directly east of those in Snake Run Cove. Westward from Snake Run Cove, exposures at Gap Mills, Monroe County, West Virginia, and north of The Narrows of New River, Giles County, Virginia, are in the continuation of the south limb of the Snake Run anticline. Small areas of outcrop west of Sweet Springs by Viola School, and west of Gap Mills near McGlone, are in the extension of the overturned north limb north of the axial St. Clair thrust fault.

Back Valley Cove lies about 5 miles south of Sweet Springs along a west-trending anticlinal structure south of Paint Bank, Virginia; the western end of the cove is in West Virginia. Sinking Creek Cove has its eastern anticlinal nose 10 miles to the south, west of Newcastle in Craig County. Ten miles farther south, Miller Cove, west of Virginia Highway 311, lies in anticlinal structure north of the trace of the Pulaski thrust fault. Catawba Valley has a homoclinal belt of outcrop a few miles southeast, above the Pulaski thrust plane and northwest of the Catawba Mountain syncline.

Northeast of Germany Cove, a cove in Hardy County east of Mathias, about 15 miles south of Moorefield, West Virginia (Woodward, 1951, p. 227), has limited exposure of middle Ordovician limestone. It is intermediate between the trend of the Western Anticlines and the outcrops in the Appalachian Valley near Broadway, Virginia.

Acknowledgments

The Graduate Funds for Research, Columbia University, supported field work in the region for periods of a few weeks each in five summers from 1940 through 1950; and a grant from The Penrose Bequest to The Geological Society of America enabled study interruptedly through 6 months in 1946. The work benefited from the observations of field companions, Lawrence C. Craig, J. Hiram Smith, Gregory W. Webb, and Victor Benavides, and from discussions with B. N. Cooper, G. A. Cooper, and H. P. Woodward. William W. Wiles drafted the illustrations.

Reference Section

The area studied adjoins that of southwestern Virginia described by Cooper and Prouty (1943), so their stratigraphic units can be applied with greatest confidence in the southwestern sections at The Narrows of the New River and in the vicinity of Gap Mills, West Virginia (Fig. 1). The Narrows section has often been described. (*See* Woodward, 1951, p. 310–311.) The writer's section along the Virginian Railroad and up a ravine to the highway is shown in Figures 2, 3, and 5, and Table 1; the thicknesses compare very closely with those of Cooper (1944b, p. 24), so that his nomenclature can be used for some of the divisions. A similar section extends from the hilltop north of the junction 3 miles southwest of Gap Mills, West Virginia, to the road south of the junction; this "Hanging Rock" section (Woodward, 1951, p. 312–313) is more nearly continuous than that at The Narrows (Table 2).

The terminology of southwestern Virginia can be applied with a few exceptions. The combined Blackford-Elway-Five Oaks unit is clearly defined at top and base, but northeastward the subdivisions are not generally recognized. The group has no local name. It might be called the "Loysburg" group after the supposed equivalent in Pennsylvania (Field, 1919, p. 410), but, as this involves

correlation, the name Lurich is proposed. The base of the "*Camarocladia* zone" of the Witten formation at The Narrows (Cooper, 1944, p. 24) and a lithic change in the middle of that disputed (Woodward, 1951, p. 206), the more conservative course seems to be to apply local names, McGlone and McGraw, to avoid ambiguity.

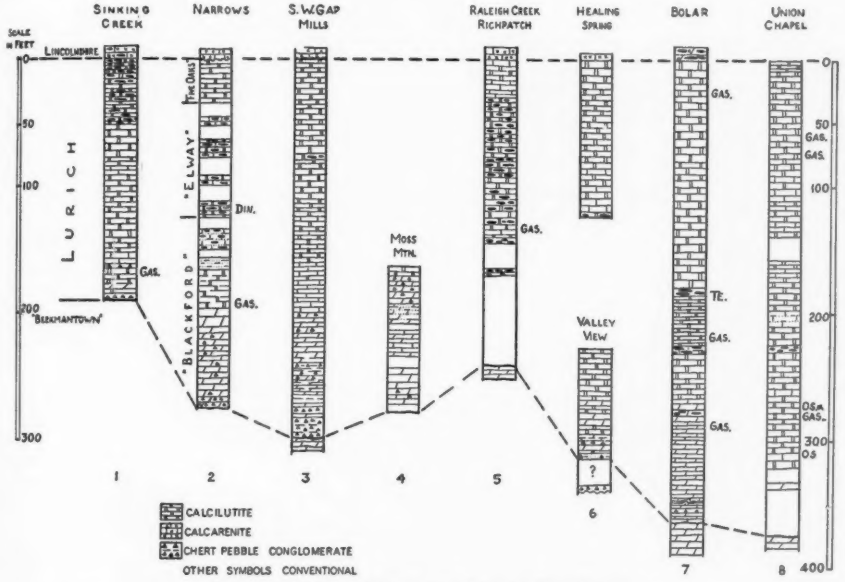


FIGURE 2.—SECTIONS OF THE LURICH FORMATION

1. Sinking Creek Cove, Crain County, Virginia, from exposures on Highway 42 above hairpin turn southwest of Fish Hatchery in eastern end of cove and in fields southeast of turn.
2. Narrows, Giles County, Virginia, along Virginian Railway east of New River north of Narrows.
3. Southwest of Gap Mills, Monroe County, West Virginia, from exposures on hill northwest of road junction 3 miles southwest of Gap Mills.
4. Moss Mountain, Monroe County, West Virginia, from exposures near Viola School, 1.5 miles west of Sweet Springs.
5. Raleigh Creek, northeastern Richpatch Cove, Alleghany County, Virginia, from exposures north of stream.
6. Healing Springs, Bath County, Virginia, from exposures just west of village.
7. Bolar, Bath, and Highland counties, Virginia, from exposures west of road 2 miles north of village in Highland County.
8. Union Chapel, Highland County, Virginia, section below and west of road about 2 miles south of chapel.

Gas—gastropods; Os—ostracods; Te—*Tetradium syringoporoides* Ulrich

zone require definition; the rocks above the Benbolt formation and below the *Camarocladia* zone, extending through "Gratton" and lower "Witten", form one unit, and a part of the "Witten" forms another; the upper "Witten" is placed within the base of the succeeding Moccasin formation expanding it slightly. The post-Benbolt, pre-Moccasin units seem lithically similar to and virtually synchronous with the Snyder and Stover limestones of central Pennsylvania, but, as this correlation has been

REGIONAL SUBDIVISION

Several contacts between contrasting lithologies can be traced in the Ordovician limestone between Pendleton County, West Virginia, and the New River at The Narrows, Virginia; they separate the section into several large stratigraphic intervals. Some additional lithic boundaries are constant for parts of this distance. Some units that seem most evident to the writer have not been thought significant by

TABLE 1.—SECTION EAST OF NEW RIVER NORTH OF NARROWS, VIRGINIA
(In feet)

	Thickness of unit	To base of formation
Trentonian Series		
"Martinsburg" formation:		
"Cuneiform beds": Well-lithified quartz-silty argillite and argillaceous quartz siltstone interbedded with shaly argillite; metabentonites of 10 inches at the base (V-7) and 10 inches at the top (V-11) with intervening thinner clays, along Highway 100, opposite north end of concrete wall	17	47
Gray, tan-weathering argillite, with thin calcitite interbeds, some with small worm borings; along highway	30	30
Eggleston formation:		
Tan, cleaved clay, metabentonite V-6 of Rosenkrans, exposed in ravine just below culvert	1.5	91
Black silicified surface on somewhat chertified ledge, on argillaceous calcilutite passing down into calcarenite, with crinoid stems, bryozoans, *Zygospira*, and *Doleroides* (?)	4	90
Grayish, yellowish-weathering argillaceous calcilutite and interbedded greenish and yellowish shaly argillite	33	86
Yellowish cleaved clay, argillite, metabentonite V-4; exposed near base of ravine	1	53
Black-rippled silicified surface on laminated buff-weathering calcilutite beds having thin argillaceous partings	1	52
Similar calcargillutite below to about 2 feet of calcareous fine quartz sandstone at base; exposed by railroad	34	51
Yellow-weathering clay, metabentonite V-3	.5	17
Carmine to pink calcargillutite with some quartz fine sandstone interbeds	12.5	16
Buff-weathering ledges of calcareous quartz fine sandstone, somewhat argillaceous toward top	4	4
Moccasin formation:		
Pink to red calcargillutite and argillaceous calcilutite, exposed only for a few feet at the top, containing abundant borings and few limestone-pebble conglomerate beds; about	200	242
Pinkish to gray argillaceous calcilutite with argillite partings	25	42
Gray to buff thin-bedded calcilutite with argillaceous partings and a few calcarenites having *Doleroides* (?); ostracode *Bollia* found in partings; upper part of "*Camarocladia* zone" of Witten formation of Cooper and Prouty	17	17
Bolarian Series		
McGraw ("Stover") formation: disconformity (Pl. 2, fig. 2):		
Camarocladia zone, lower part, of Cooper: Gray to buff-weathering massive-ledged thin-bedded calcitite, principally fine-textured, somewhat argillaceous, but with a few calcarenite lenses; irregular bedding, with holes weathered from *Camarocladia* tubes; a very resistant unit; well exposed in railroad cut	16	16
McGlone ("Snyder") formation:		
Cryptophragmus zone of Witten formation of Cooper: Gray calcarenite, somewhat shaly and argillaceous toward base, with frequent *Cryptophragmus*, a tubular alga	11	100
Yellowish-weathering finely laminated argillaceous calcilutite; to base exposure at north end of cut	9	89
Unexposed across ravine; about	80	80
Benbolt formation:		
Gray, well-bedded argillaceous calcisiltite with rounded lenses and nodules of black chert abundant; in ravine at south end of cut	24	184
Dark, impure calcisiltite, heavy-ledged, with abundant nodules of black chert, toward top, few at base; south end of railroad cut	23	160
Dark, heavy-ledged impure calcitite, mostly silt-textured, but variable; fossiliferous zones with bryozoans, brachiopods; *Girvanella* abundant in 4-foot massive calcarenite ledge at top; well exposed in railroad cut	94	137
Dark, impure calcisiltite and carcarenite, heavy-ledged, with few black chert nodules at several horizons; lower boundary not readily defined near north end of cut	43	43

TABLE 1.—*Continued*

	Thickness of unit	To base of formation
Peery formation:		
Dark calcisiltite having irregular argillaceous patches, weathering to depressions; poorly bedded; with abundant nodular chert; exposed from 5 feet above prominent overhang to north end of cut; probably nearly complete	29	29
Ward Cove formation:		
Concealed in ravine between railroad cuts, about	80	120
Dark-gray, bluish-gray-weathering argillaceous calcisiltite, poorly bedded	25	40
Dark gray argillaceous calcisiltite with small nodules of black chert, well exposed at south end of cut	15	15
Chazyan Series		
Lincolnshire formation:		
Gray, white-weathering, platy calcilutite, becoming coarser-textured and darker downward	13	47
Dark, brownish-weathering impure calcarenite with large masses of black chert, heavy-ledged	20	34
Gray calcarenite, penetrating at base into underlying bed	14	14
Disconformity		
Lurich formation:		
Five Oaks member:		
Light-gray, white-weathering calcilutite with some stylolitic laminae; worm borings; *Tetradium* rare	35	275
Elway member:		
Very poor and disturbed exposures of *Dinorthis*-bearing black cherty calcitite; probably affected by cavern collapse, estimated	77	240
Gray, light-weathering calcilutite with black chert and *Dinorthis*	15	163
Blackford member:		
Gray, quartz-silty calcitite with black chert nodules; poorly exposed along lane east of railroad	30	148
Ashy-gray silicisiltite with chert nodules	10	118
Gray, well-bedded impure calcilutite, gastropods near base	30	108
Gray, buff-weathering heavy-ledged dolomite, exposed just south of railroad cut	14	78
Well-bedded tan-weathering gray dolomite with scattered chert fragments	22	64
Similar dolomite, with abundance of chert pebbles forming conglomerate in the basal few feet	42	42
Disconformity, on north side of small fault, 150 feet north of roadway crossing.		
Canadian Series		
Buff-weathering heavy-ledged dolomite rock in main bluff along railroad		

other geologists. The writer's measurements of the lower part of the section along the New River at Narrows (Table 1) agree very closely with those published by B. N. Cooper (1944b, p. 24); Cooper applied the nomenclature of southwestern Virginia.

The lowest constant lithic change in the southwestern sections (Fig. 2) is between a white-weathering gray calcilutite[1] of the Five Oaks formation and overlying darker-weathering, black chert nodule-bearing argillaceous calcitite of the Lincolnshire. At places a lower contact is recognizable where chert-pebble-bearing grayish and reddish siliceous silty rocks of the Blackford overlie buff-weathering dolomite of the "Beekmantown". The Elway black chert-bearing calcilutite separates the two. Northeastward, the three-fold Blackford-Elway-Five Oaks sequence lacks chert-pebble conglomerate at the base and becomes dolomite grading into calcilutite; a new name, Lurich formation, is applied. The Lurich resembles the Loysburg formation of Pennsylvania; the "Beekmantown"-Loysburg contact is similarly obscure. Cephalopods in the "Beekmantown"

[1] The rock term claystone carries connotation of argillaceous or clay mineral content, and siltstone and sandstone, of quartz content; hence lutite, siltite, and arenite are used to avoid ambiguity. "A long word should not be avoided when it is the apt one.... In scholarly writing and even elsewhere big words are often the most economical ones, for they ... say a great deal in a small space" (McCartney, 1953, p. 6, 8).

TABLE 2.—SECTION ALONG HANGING ROCK ROAD SOUTH OF ROAD JUNCTION 3 MILES SOUTHWEST OF GAP MILLS, WEST VIRGINIA, AND ON HILLS TO THE NORTH
(In feet)

	Thickness of unit	To base of formation
Trentonian Series		
"Martinsburg" formation:		
Shaly calcareous argillite with interbeds of calcarenite and coquina		
"Cuneiform zone": well-lithified, jointed siliceous silty argillite, having 3-foot clay (V-7) at top of basal 3–4-foot heavy cuneiform jointed bed, and a pair of thinner metabentonites (V-10 and V-11) 9 and 10 feet higher	14	51
Shaly argillaceous calcitite with few interbeds of worm boring-bearing calcisiltite, calcarenite, and coquina with *Sowerbyella* and "*Dalmanella*" sp., as in a thin bed 6 inches from base	36	37
Conglomerate with calcitite pebbles	1	1
Eggleston formation:		
Greenish quartz-silty argillite with few interbeds argillaceous calcisiltite, some with minute worm borings	23	86
Brownish clay metabentonite (V-4), poorly exposed	2.6	63
Brownish to greenish silty argillite in beds of 1 to 6 inches; top surface with chert patches; well exposed in field above road	25	60
Greenish-calcite-flecked heavy-ledged argillutite	4	35
Greenish argillite with thin calcareous zones; in ledges several feet thick	24	31
Greenish-brown quartz-silty argillite in heavy ledge	5	7
Buff-weathering argillaceous quartz arenite exposed at upper end of sharp left turn in road	2	2
Moccasin formation:		
Red calcargillutite with some buff intervals; ripple marks and mud cracks in lower beds	26	181
White well-bedded calcilutite with reddish and buff argillitic partings	6	155
Red calcargillutite with interference ripple marks in upper part	12	149
Light-gray argillaceous calcilutite with reddish argillaceous partings	3	137
Red calcargillutite overlain by mud-cracked argillaceous calcilutite having calcitite pebbles at top	8	134
White calcilutite, well-bedded, having buff argillite partings; *Tetradium* sp. in 12-inch bed above 7 feet in unit	16	126
Buff calcilutite becoming buff shaly argillite with argillaceous calcitite interbeds	12	110
Buff shaly argillutite with few thin calcitite beds	12	98
Red calcargillutite poorly exposed at base, overlain by a few feet of buff calcargillutite	34	86
Buff marly argillaceous calcilutite, thin-bedded, with some mud-cracked zones	30	52
Gray dense calcitite with buff-weathering argillaceous partings and interbeds; fucoidal	22	22
Bolarian Series		
McGraw formation:	15	22
Dark-gray dense blocky-breaking ledges of calcitite having fucoidal *Camarocladia*	7	7
McGlone formation:		
Gray laminated calcitite, with *Cryptophragmus* on upper few feet, exposed at turn in road	8	8
Benbolt formation:		
Calcisiltite and calcarenite, partly rippled cross-laminated	10	106
Calcisiltite, laminated with some contorted bedding	9	96
Dark somewhat siliceous calcisiltite and calcarenite in thin beds with argillaceous partings	55	87
Dark siliceous calcarenite and calcisiltite with *Tetradium*, *Stromatocerium*, and *Dystactospongia*; somewhat biohermal, particularly massive in area just east of road; base of good exposure along road, but immediately overlying cherty beds exposed to east of road in quarried cliff	32	32
Peery formation:		
Light-weathering dark calcilutite containing gastropods and the pteropod *Polylopia*	5	29
Dark calcilutite with lenses and nodules of black chert; base of exposure in ravine east of road	24	24

TABLE 2.—*Continued*

	Thickness of unit	To base of formation
Ward Cove formation:		
Field ledges of siliceous silty and argillaceous calcitite having abundant brachiopods in some beds; scattered chert nodules becoming abundant in basal 35 feet; rather small spheroidal to ellipsoidal black nodules in dark-gray well-bedded siliceous argillaceous calcitite; best exposures about a quarter of a mile east of road; several computed measurements average about	175	175
Lincolnshire formation:		
Field ledges west of road principally of impure, siliceous calcarenite containing a few beds with irregular black chert nodules; sharp contact with underlying calcilutite along irregularly sinuous surface in road cut west of junction; half a mile east of road, upper beds are reefy, biohermal, with *Billingsaria* common; little chert; formation thins eastward and is missing just south of large sink a mile east of road; thickness in sections within half a mile of road is about	45	45
Lurich formation:		
Five Oaks member:		
White-weathering calcilutite, pure, well-bedded; exposed on hill slope above Lincolnshire quarry a quarter of a mile west of road junction; about	100	295
Elway member:		
White-weathering gray calcilutite, having abundant black chert in beds and lenses of upper part, overlying darker medium-textured calcitite; in upper part of hill slope; about	90	195
Blackford member:		
Buff-weathering laminated medium-textured dolomite having nodular and irregular masses of chert in upper part; small chert fragments infrequent	55	105
Buff-weathering siliceous quartz-silty dolomite and reddish dolomitic quartz siltite, having chert fragments and interbeds of chert-pebble conglomerate; at hill crest	50	50
Disconformity		
Canadian Series		
Buff-weathering well-bedded dolomite		

where it is succeeded by basal Lurich chert-pebble conglomerate indicate that the "Beekmantown" is lower Ordovician Canadian.

Much higher in the sequence is 30 feet or less of medium-gray-weathering, dark, somewhat argillaceous calcilutite, irregularly laminated with buff-weathering rodlike structures; it is resistant and brittle and breaks into rectangular blocks along joints cutting the rather thick beds. It is succeeded abruptly by less-resistant, variably argillaceous, and frequently quartz-silty calcitite. The contact is a pitted surface, evidently a disconformity. This contact, which has seemed so evident to the writer, falls within the "*Camarocladia* zone" of the "Witten limestone" in The Narrows section. The underlying unit forms only an unnamed part of the "Witten". This upper unit is so similar to the Stover limestone of Pennsylvania that the writer has so classified it; but as this involves correlation, the rock is called the McGraw limestone.

The interval from the Five Oaks to the top of the McGraw in southwestern Virginia contains in succession the Lincolnshire, Ward Cove, Peery, Benbolt, Gratton, and Wardell formations and most of the Witten formation (Cooper and Prouty, 1943). The Lincolnshire seems distinct throughout the area studied, though lithic contrast with the succeeding Ward Cove is not everywhere marked. The writer believes he can trace the cherty Peery along sections to the northeast. A higher zone of cross-bedded fine arenite calcite and quartz grains persists and is considered the top of the Benbolt. The "Gratton" and the lower "Witten" below the McGraw "*Camarocladia* zone" at the New River are considered a unit. Thus the rocks from the sharp break above the Five Oaks to the contact at the top of the cross-bedded zone lie in the position of the Lincolnshire, Ward Cove, Peery, and Benbolt formations of southwestern Virginia. The last three are so difficult to separate in the northern sections in Highland and Pendleton counties that they can more conveniently be classed as a single formation,

TABLE 3.—SECTION EAST OF IRON HILL, SNAKE RUN COVE, ALLEGHANY COUNTY, VIRGINIA

Lower part of section, through Peery formation, measured on slope above jog in road just east of farmhouse half a mile east of Iron Hill junction; succeeding beds exposed higher on same slope, but measured at better exposure just east of farmhouse half a mile farther eastward. Thicknesses in feet.

	Thickness of unit	To base of formation
Trentonian Series:		
"Martinsburg" formation:		
Silicified ledge beneath probable metabentonite above crest of hill slope; overlying little-exposed shaly impure calcisiltite and calcarenite		
Eggleston formation:		
Silicified argillaceous calcitite with some branching bryozoans, underlying metabentonite V-6	1	85
Buff-weathering argillaceous calcilutite with interbeds of calcisiltite and a few limestone-pebble conglomerates	32	84
Somewhat silicified ledge of laminated calcilutite with thin calcite seams, underlying metabentonite V-4	1	52
Buff-weathering argillaceous calcilutite	49	51
Buff bedded quartz sandstone	2	2
Moccasin formation:		
Reddish and buff calcargillutite with thin calcilutite interbeds; few desiccation-cracked and ripple-marked beds	60	158
White-weathering calcilutite, with some argillite partings	12	98
Buff-weathering argillaceous calcilutite, calcite-flecked in upper 15 feet	53	86
Gray calcilutite with argillaceous partings, some limestone conglomerate and few calcarenite beds	33	33
Bolarian Series		
McGraw formation:		
Heavy ledges of dark calcilutite with calcarenite lenses, *Cryptophragmus* present in lower beds, *Camarocladia*-bearing	7	7
McGlone formation:		
Buff-weathering, gray calcilutite, laminated	21	21
Benbolt formation:		
Gray, quartz arenitic calcisiltite, beautifully cross-laminated	9	183
Dark impure heavy-ledged calcisiltite	34	174
Dark impure calcisiltite and calcarenite with *Foerstephyllum* in upper beds, brachiopods and bryozoans in underlying beds, *Sowerbyella*, *Multicostella*; thickness measured as 161 feet in the western of the two sections	140	140
Peery formation:		
Dark quartz, silty and argillaceous well-bedded calcisiltite with black chert nodules	26	26
Ward Cove formation:		
Dark, thin-bedded argillaceous calcisiltite, sparingly fossiliferous; having lensing argillitic seams, basal contact exposed along roadside east of farmhouse	55	55
Lincolnshire formation:		
Dark, heavy-ledged, black chert-bearing, impure calcisiltite and calcarenite interruptedly exposed from just above road to slope below it, about	83	83
Lurich formation:		
Five Oaks member:		
White-weathering gray calcilutite		

called the "Hatter" formation from the supposed Pennsylvania equivalent. The unit extending from the top of the cross-laminated Benbolt to the base of the *Camarocladia*-bearing McGraw seems most like the Snyder limestone of central Pennsylvania, and has been so called, but as this is a correlation, the local name McGlone will be applied, with type section near McGraw Gap.

The rocks succeeding the McGraw limestone in the southwestern sections differ greatly from those in the northeast. In the southwest, con-

TABLE 4.—SECTION IN EASTERN RICHPATCH COVE, ALLEGHANY COUNTY, VIRGINIA

Trentonian measured along side road 620 north of highway about a mile west of Richpatch Church junction; also well shown half a mile east of northeast gap. Benbolt and McGlone measured west of road by southeast gap toward Eagle Rock. Underlying beds measured along Raleigh Creek on gently dipping exposures near Northeast gap. Thicknesses in feet.

	Thickness of unit	To base of formation
Trentonian Series		
Martinsburg formation:		
Tan-weathering calcareous argillite, few limestone interbeds; metabentonite V-7, 3 feet above base		
Tan-weathering argillaceous beds with interbeds of argillaceous calcisiltite with small worm borings, and of calcarenite with *Sowerbyella*, *Zygospira*, and *Doleroides* (?), some beds with *Sinuites*	40	40
Eggleston formation:		
Brown, somewhat mineralized, bryozoan-bearing argillaceous calcilutite overlying interbedded argillite and calcitite, shaly; probably has overlying metabentonite, shown in excellent sections both east and south of Covedale Chapel in western Richpatch	27	50
Tan-weathering clay, metabentonite V-4	2	23
Buff-weathering, thin-bedded argillaceous calcilutite having thin nodular bed of limestone-pebble conglomerate	19	21
Buff-weathering medium quartz arenite	2	2
Moccasin formation:		
Buff-weathering shaly calcargillutite	26	50
White-weathering rather pure, plane-bedded calcilutite	6	24
Buff-weathering somewhat laminated argillaceous calcilutite, base 100 yards from highway	18	18
Disconformity		
Bolarian Series		
McGlone formation:		
Heavy ledges of calcite-flecked calcilutite, becoming finer-laminated toward the base	12	12
Benbolt formation:		
Gray, quartz-silty calcisiltite or fine arenite, finely cross-laminated, particularly toward top; at top of good exposures along Raleigh Creek	16	126
Gray calcarenite, containing occasional *Foerstephyllum*, somewhat finer-textured in lower part	32	110
Gray, irregularly bedded impure calcitite, mostly silty-textured with brachiopods and bryozoans in some beds, heavy-ledged	78	78
Peery formation:		
Dark, heavy-ledged impure calcitite with black chert nodules (Pl. 1, fig. 3), fossils abundant in some beds, *Polylopia* in several horizons from near base at top in section on crest of hill west of road by southeast gap, and in ravine to west; thickness by spring along Raleigh Creek, about	46	46
Ward Cove formation:		
Dark, well-bedded argillaceous calcitite; few black chert nodules	7	249 (255′ at SE Gap)
Dark calcareous and argillaceous siltstone, with abundant *Sowerbyella* in several zones; leached residue leaves fossils and dark silty mud	130	242
Dark, well-bedded argillaceous calcisiltite with few chert nodules; *Nidulites* and *Receptaculites* in several beds	90	112
Dark argillaceous calcitite, somewhat shaly, with abundant ellipsoidal chert nodules; exposed where stream nears road; *Dystactospongia* abundant in upper part of this zone east of Covedale Chapel in west Richpatch	22	22
Chazyan Series		
Lincolnshire formation:		
Dark, medium- to coarse-textured impure calcitite with abundant black chert in irregular lenses and beds; *Sowerbyites* abundant in upper beds east of road, and near top of good exposures about 50 feet from base in ravine west of road; latter section of lower beds principally calcarenitic with abundant black chert, and frondescent bryozoans, *Pachydictya* sp.	107	107
Disconformity		
Lurich formation (undivided):		
White-weathering, well-bedded calcilutite	18	235
White-weathering, dark calcilutite with abundant black chert in nodules and beds, forming bluff along west of creek, to base of exposure	110	217
Concealed, computed across road and creek	107	107
Canadian Series		
Buff-weathering heavy-ledged dolomite exposed east of road		

TABLE 5.—SECTION NEAR MCGRAW GAP, IN SOUTHERN WARM SPRINGS COVE, NORTHERN ALLEGHANY COUNTY, VIRGINIA

Measured and computed eastward near sinks along lane a quarter of a mile east of farmhouse a mile south-southeast of Sinking Spring Church on highway 220. Thicknesses in feet.

	Thickness of unit	To base of formation
Trentonian Series		
Eggleston formation:		
Tetradium fibratum exposed in zone on east slope of ridge 21 feet from base		
Buff-weathering quartz arenite, poorly exposed above easternmost good limestone exposures on crest of ridge		
Moccasin formation: (interrupted exposure; better 1.5 miles southwest of church)		
Buff-weathering argillaceous calcilutite, some "mud-cracks" and shaly partings; about	80	160
White-weathering calcilutite with some argillite interbeds; *Tetradium*-bearing; about	56	80
Calcilutite with interbeds of calcarenite and argillite; and some reddish argillite; containing *Solenopora, Tetradium cellulosum* (Hall)	24	24
Disconformity		
Bolarian Series		
McGraw formation; type section:		
Heavy-ledged dense dark calcilutite with interbeds of lensing calcarenite; contains *Camarocladia*	9	9
McGlone formation; type section:		
Buff-weathering gray calcilutite, principally finely laminated, having a few argillaceous partings, about	27	62
Interbedded dark-gray, dense calcitite and calcarenite, much of it strongly cross-laminated; bearing *Stromatocerium* in exposures near orchard to northeast; about	35	35
Benbolt formation:		
Ripple-marked finely laminated dark quartz-sandy calcarenite and calcisiltite	5	129
Dark dense calcitite with some cross-laminated calcarenite, interbeds	20	124
Dark, impure, well-bedded to wavy-bedded calcitite	21	104
Calcarenite, irregularly bedded and somewhat cross-laminated, with large masses of bryozoans, and the coral *Foerstephyllum* sp.	16	83
Calcisiltite and calcarenite, irregularly bedded and quite fossiliferous, somewhat biohermal, with *Receptaculites, Foerstephyllum*, bryozoans, and brachiopods	67	67
Peery formation:		
Dark, somewhat siliceous calcisiltite with black chert nodules irregularly distributed; poorly exposed on southeast slope east of point where stream crosses trail and flows into sink, about	36	36
Ward Cove formation:		
Concealed in area of large sink; along fence of orchard to northeast, it is computed as about	50	120
Dark, siliceous silty and somewhat carbonaceous shaly calcitites bearing *Gonioceras, Nidulites, Receptaculites*; lower beds exposed west of sink; measured along fence	62	70
Dark, somewhat siliceous calcisiltite with black chert nodules; 6.5 feet east of farmhouse, to a maximum of	8	8
Disconformity		
Chazyan Series		
Lincolnshire formation:		
Variable unit of reefy structures having *Billingsaria*, bryozoans, and stromatotoporoids, with laminated, *Basiliella*-bearing calcilutite, channels filled with calcarenite; forming knobby exposures on crest of ridge by road (Pl. 1, fig. 2)	70	140
Heavy ledges with black chert; calcarenite and calcisiltite	70	70
Lurich formation:		
Dark, white-weathering calcilutite		

spicuous red rocks lie above the McGraw, but in the northeast the rocks are more somber buff and gray weathering. The basal quartz sandstone and several metabentonites of the Eggleston that overlie the red sediments can be traced through into Warm Springs Cove, so that continuity is established in spite of the changes to the buff facies. Beyond, in Highland and Pendleton counties, fossiliferous limestone, formerly called "Oranda", with associated metabentonites is in about the same position as the Eggleston. It is similar to the Oranda formation of the Shenandoah Valley, but the local term Onego is applied. The rocks between the Onego and the top of the McGraw are essentially like the Nealmont formation of Pennsylvania and are so classified, and the Onego and succeeding beds are faunally and lithically like the Salona formation of Pennsylvania. Thus the Moccasin, Eggleston, and Martinsburg of The Narrows section correspond to the Nealmont and Salona formations of the northeast.

TABLE 6.—SECTION IN SOUTH SLOPE OF HILL WEST OF HEALING SPRING, BATH COUNTY, VIRGINIA
(In feet)

	Thickness of unit	To base of formation
Trentonian Series		
"Martinsburg" formation:		
Dark, calcareous and quartz-silty argillite and calcitite, west of syncline and anticline exposing underlying beds three times		
Thin poorly exposed metabentonite, probably sheared to less than true thickness, about	.2	137
Thin-bedded argillaceous calcisiltite with some coquinal beds and a few calcitite-pebble conglomerate; cherty at very top; about	43	137
Thin metabentonite, poorly exposed, thickness probably reduced by shearing	.2	
Dark calcisiltite with argillite interbeds and coquinas with gastropods, and with *Dalmanella* and *Sowerbyella*; cherty at very top	22	94
Dark, somewhat calcareous and siliceous argillite, having doubtful metabentonites at base and top, and distinct 6-inch clay lying on cherty surface 5 feet from base of unit; probably the "cuneiform" zone of sections to the southwest	11	72
Thin beds of argillaceous calcitite, some with gastropods and trilobites, and calcitite conglomerates in middle and at base	13	61
Dark, well-bedded, shaly calcisiltite beds, some with worm borings, others with gastropods	48	48
Eggleston formation:		
Thin clay, probably metabentonite V-6		
Buff-weathering argillaceous calcilutite with argillaceous partings and interbeds; *Foerstephyllum* heads at about 23 feet in unit	43	89
Buff-weathering rather massive calcargillite, having masses of *Tetradium fibratum*, about 10 feet from base of the unit	27	46
Thin metabentonite, probably V-3	1	19
Buff-weathering argillite with calcilutite interbeds	16	18
Buff, argillaceous quartz sandstone	2	2
Moccasin-Nealmont formation:		
Buff- to white-weathering plane-bedded argillaceous calcilutite and calcilutite, some beds with desiccation cracks, chert in bottom bed	32	117
Buff metabentonite clay; almost	1	85
White calcilutite with buff-weathering argillaceous interbeds; *Tetradium cellulosum* in several of beds in upper 15 feet; base of exposure along lane south of barn	84	84
Bolarian Series		
McGraw formation:		
Poorly exposed along lane		

The contact of the McGraw with the Trentonian Moccasin and Nealmont formations has been distinguished from that of the type Witten southwest of Tazewell to central Pennsylvania. Throughout this distance, the basal beds are shaly limestones and calcareous siltstones in which *Doleroides* sp. and *Pionodema* sp. persist; in nearly every exposure of this contact, the fossils are in thin beds within a foot of the base of the Nealmont or Moccasin. The underlying ledges are of the more resistant, heavier-ledged, *Camarocladia*-bearing McGraw limestone. Similar *Camarocladia*-bearing ledges form occa-

TABLE 7.—SECTION NEAR BOLAR, BATH AND HIGHLAND COUNTIES, VIRGINIA

Section of Trentonian principally from north of Jack Mountain road in Bath County, .6 mile east of Bolar; lower beds from hill slope west of road in Highland County, 2.1 miles north of Bolar. Thicknesses in feet.

	Thickness of unit	To base of formation
Trentonian Series		
Onego ("Oranda") member, Salona formation:		
Dark, well-bedded argillaceous calcilutite, quite fossiliferous in some horizons; *Leptaena, Opikina, Hesperorthis, "Dalmanella", Doleroides* (?), *Sowerbyella;* about	3	70
Interrupted exposure, occasional beds with *"Dalmanella"* and *Sowerbyella*; about	67	67
Base of Onego formation not determinable		
Nealmont-Moccasin formation:		
Buff-weathering argillaceous calcilutite; some desiccation cracks in upper beds; calcite-flecked beds in middle; *Tetradium* sp. cf. *I. racemosum* Raymond and *T. cellulosum* Hall in calcilutite interbeds in lower 10 feet	35	199
Calcilutite, principally well-bedded, rather pure, white to buff weathering, with some buff, argillaceous partings; exposed well also on slope 2.1 miles north of Bolar	105	164
Calcilutite like that above, having calcarenite interbeds with abundant fossils—species of *Rhynchotrema, Zygospira, Doleroides* (?), and ostracoda, exposed north of Bolar	29	59
Unexposed in either section; contact not seen	30	30
Bolarian Series		
McGraw formation:		
Heavy ledges of dark calcilutite with *Camarocladia*; higher beds poorly exposed, about	15	15
McGlone formation:		
Dark-gray, buff-weathering laminated impure calcilutite	14	49
Heavier-ledged white-weathering calcilutite	35	35
Benbolt formation:		
Dark, quartz-sandy calcitite, with fine cross-lamination, with laminated and some contorted beds toward base	9	144
Dark, quartz-silty, rubbly weathering calcisiltite and calcarenites; *Dystactospongia* to top; *Foerstephyllum*, large masses of *Mesotrypa*; *Girvanella* near base	135	135
Peery formation:		
Dark impure calcisiltite with black chert nodules, poorly exposed for about	9	9
Ward Cove formation:		
Dark, impure, well-bedded calcisiltite, with few calcarenite interbeds; *Sowerbyella* common near base	40	45
Dark, shaly argillaceous calcilutite with black chert nodules	5	5
Disconformity		
Chazyan Series		
Lincolnshire formation:		
Light-gray, quite pure, coarse calcarenite, having nonpersistent calcilutite lenses in the upper beds	20	50
Gray calcarenite with large irregular masses of black chert	30	30
Disconformity		
Lurich formation:		
Five Oaks member:		
White-weathering quite impure calcilutite, incompletely exposed		

sional interbeds in the Nealmont-Moccasin. The Moccasin lies on older Bolarian beds in Sinking Creek, Back Valley, and Richpatch coves; the base is argillaceous quartz sandstone on doubtful McGlone in the eastern end of Sinking Creek Cove, and calcareous argillite on McGlone in the other two areas.

The stratigraphic relations are summarized

in the restored sections of the Chazyan and Bolarian series (Fig. 4) and of the lower Trentonian series (Fig. 6).

TABLE 8.—SECTION NEAR TRIMBLE IN NORTHERN BOLAR COVE, HIGHLAND COUNTY, VIRGINIA

McGlone, Nealmont, and Onego formations measured from east side of apple orchard north of house .3 mile southeast of Trimble to stream bank by road northwest of house; older beds exposed east of anticlinal core, .3 mile east of same house. Thicknesses in feet.

	Thickness of unit	To base of formation
Trentonian Series		
"Martinsburg" formation:		
Dark calcareous argillite with calcareous interbeds exposed along stream		
Onego member, Salona formation:		
Dark chert surface underlying probable metabentonite, and succeeding shaly thin-bedded somewhat argillaceous calcitite having occasional fossils; *Leptaena, Opikina*, and other forms listed in Table 14	37	249
Similar argillaceous calcitite, some *Sowerbyella* coquina; to another reentrant	14	212
Poorly exposed buff-weathering argillaceous calcilutite along stream bluff and old road; base of Onego within this interval	54	198
Nealmont formation:		
Top unexposed in above interval		
Thin beds of buff-weathering impure calcilutite, basal exposures by roadside at fence	29	144
Similar to overlying beds east of fence, including dark calcisiltites in lower part	55	115
Argillite and calcitite of varying texture with *Tetradium fabratum, Solenopora*, and *Zygospira*; calcarenitic, particularly in lower part	44	60
Granular silty calcitite with *Pionodema* in basal beds near east edge of orchard	16	16
Disconformity, irregularly eroded surface		
Bolarian Series:		
McGraw formation:		
Dark, heavy-ledged bedded calcitite, *Camarocladia* bearing, exposed in stream northeast of house, and .3 mile east on gently dipping east limb of anticline	26	26
McGlone formation:		
Dark, thin-bedded calcilutite	14	65
Gray, laminated calcilutite, becoming granular with *Cryptophragmus* in lower part	13	51
Calcilutite, interruptedly exposed; *Girvanella*	38	38
Benbolt formation:		
Cross-laminated, somewhat quartz-silty calcisiltite, succeeding calcarenite in heavy ledges containing heads of *Foerstephyllum* and *Tetradium*, and *Receptaculites* and *Dystactospongia*; interruptedly exposed on hillside east of anticlinal core in Ward Cove limestone.		

CHAZYAN SERIES

Lurick Formation

The top of the lowest part of the Ordovician limestone sequence is white-weathering calcilutite that contrasts sharply with siliceous cherty calcarenite. The calcilutite, of variable thickness, passes down into beds having nodular black chert; these beds overlie impure dolomite (Fig. 2). From Bolar southwestward, chert-pebble conglomerate zones are within and at the base of the dolomite. To the southwest the sequence is continuous upward from Blackford (Butts, 1942) chert-pebble conglomerate and dolomite with ashy-gray and reddish siliceous siltstone to Elway (Cooper, 1951), *Dinorthis*-bearing calcitite with abundant black chert, to Five Oaks (Cooper and Prouty, 1943) calcilutite; these three units with younger formations formed the Cliffield group (Cooper and Prouty, 1943), subsequently suppresed (Cooper, 1951). The Loysburg formation (Field, 1919) in Pennsylvania, with Clover (Kay, 1941;1943) calcilutite at the top, is very like the northern sections in the Virginias. In the Appalachian Valley to the east, the term St. Paul group has been proposed for essentially the same sort of

sequence (Neuman, 1951). The unit does not have a local name in the area of study so is here designated the Lurich formation, or Lurich group where separable into formations.

The Lurich is middle Ordovician, and most have classed it as Chazyan, though the upper St. Paul calcilutite has been thought to be the equivalent of part of the Black River group of New York (Neuman, 1951), and thus Bolarian. The underlying rocks are dolomite, rarely fossiliferous near the Lurich. A fauna of Canadian cephalopods from the few score feet of exposed underlying strata in the core of the Bolar anticline 1½–2 miles northeast of Bolar in Highland County, Virginia, comprised *Campbelloceras brevicameratum* Ulrich, Foerste, Miller, and Furnish, *Eurystomites bolarensis* U., F., M., and F., and *Trochilitoceras bevani* U., F., M., and F., believed of Powell age, thus rather high in the Canadian or Beekmantownian series (Ulrich, Foerste, Miller, and Unklesbay, 1944, p. 16–17).

TABLE 9.—SECTION NEAR MILL GAP AND LOWER GAP, SOUTHERN BLUEGRASS COVE, HIGHLAND COUNTY, VIRGINIA

Onego formation from hill slope west of anticlinal axis north of ravine .5 mile east of Lower Gap; Nealmont, from east of axis north of ravine and road 1 mile east of Mill Gap and west of axis 1 mile southeast of gap; also fully exposed east of Lower Gap. Thicknesses in feet.

	Thickness of unit	To base of formation
Trentonian Series		
"Martinsburg" formation:		
Scattered exposures in many localities; bearing *Sinuites, Amplexograptus, Resserella* in interbedded calcarenite and argillaceous calcilutite east of anticlinal axis east of Lower Gap.		
Onego member, Salona formation:		
Brown-weathering 11-inch ledge of 2-inch beds of argillaceous calcilutite lying on 3-inch coquina with *Hesperorthis, Opikina, Sowerbyella,* and *Resserella*; probably underlies metabentonite	1	46
Gray, somewhat shaly calcilutite, with occasional fossils listed in Table 14	29	45
Gray, somewhat shaly argillaceous calcilutite with calcarenite interbeds becoming frequent near base	16	16
Nealmont formation:		
Grayish, buff-weathering argillaceous calcilutite, not fossiliferous	70	275
White-weathering, thin-bedded calcilutite, at east end of hillside exposure east of Lower Gap; underlying beds best exposed 1 mile southeast of Mill Gap, and north of lane 1 mile east of gap: thin beds of white- and buff-weathering calcilutite and calcitite of calcilutite granules; about	80	205
Variable locally; calcitite having zones of calcarenite with rolled masses of *Foerstephyllum, Tetradium fibratum,* and *Solenopora,* and abundant brachiopods in some zones, including *Hesperorthis, Leptaena* sp. cf. *L. charlottae* and *Rhynchotrema*; some marly calcilutite interbeds, and calcitite-pebble conglomerates; base not well exposed; about	125	125
Disconformity		
Bolarian Series		
McGraw formation:		
Dark, heavy-ledged calcilutite, *Camarocladia* bearing, and with few nodules of black chert; well exposed east of anticline 1 mile southeast of gap	27	27
McGlone formation:		
Calcitite, principally fine-textured; *Cryptophragmus* abundant near top in several localities; also *Stromatocerium* and *Tetradium cellulosum* (Hall)		

Although the sequence within the Lurich is from dolomite through black-chert-bearing calcitite into pure calcitite, and these correspond roughly to the Blackford, Elway, and Five Oaks formations in southwestern Virginia, such subdivision does not seem warranted northeast of Monroe County, West Virginia. The thickness of the Lurich is generally about 300 feet, but that of the subdivisions varies considerably. Probably the Clover calcilutite of Pennsylvania and the calcilutite exposed in the core of the Germany Settlement anticline in Pendleton

TABLE 10.—SECTION NORTH OF BLUEGRASS, HIGHLAND COUNTY, VIRGINIA

Thickness measured and computed from interrupted exposures on hill a quarter of a mile north of Bluegrass; additional lithic description from roadside cuts 1.25 miles north-northwest, 1.5 miles northwest, and north of road junction 2 miles northwest of Bluegrass-Crabbottom on older maps. Thicknesses in feet.

	Thickness of unit	To base of formation
Trentonian Series		
Salona formation:		
Dark, buff-weathering argillaceous calcisiltite, well bedded, with few fossils; *Cryptolithus* sp., "*Dalmanella*" sp. in interrupted exposure.		
Unexposed but presumed metabentonite at base		
Onego member, Salona formation:		
Silicified black, brown-weathering argillaceous calcisiltite, forming ledge cropping out on hill slope near isolated locus tree; species of *Leptaena, Sowerbyella, Opikina, Hesperorthis*; also exposed just east of fence by stream to south	2	45
Poorly exposed shaly calcitite, passing down into argillitic calcarenite with *Tetradium* sp. cf. *T. clarki* west of fence near stream	43	43
Nealmont formation:		
Dark, plane-bedded, somewhat argillaceous calcitite with some *Tetradium cellulosum*-bearing calcilutite; desiccation structures in some beds; best exposed along roadside 1.5 miles northwest of Bluegrass; about	40	250
Light-gray calcarenite, heavy-ledged, sparsely fossiliferous, exposed with underlying beds on hill 1.2 miles north-northwest of Bluegrass; *Leptaena* sp. cf. *L. charlottae*, like that found in Rodman of Pennsylvania	24	210
Greenish to buff metabentonite, N-2, on silicified surface; exposed also interruptedly on hill north of Bluegrass	1	186
Light-gray calcarenite, about	15	185
Gray calcisiltite in thin beds, nonfossiliferous	30	170
Buff-weathering metabentonite, N-1	1	140
Dark, brown-weathering silicified limestone ledge, cherts somewhat angular in form, best west of hillcrest 1.2 miles from Bluegrass, but sparsely on hillside north of town	2	139
Thin beds of buff-weathering dark-gray argillaceous calcisiltite with a few fossiliferous shaly partings having *Doleroides* (?), *Sowerbyella*, and *Hesperorthis*; most continuous exposures north of junction 2 miles northwest of Bluegrass, and along stream half a mile north of town; section does not extend to base, and latter has rarely exposed basal silty beds in contact with McGraw limestone; about	137	137
Disconformity		
Bolarian Series		
McGraw formation:		
Gray, resistant, massive-ledged, cliff-forming calcisiltite with calcarenite lenses and rodlike buff-weathering silty structures, *Camarocladia* sp., weathering to holey surfaces; contrasts topographically with sod-covered basal Nealmont on hill slope north of Bluegrass	27	27
McGlone formation:		
Thin-bedded, resistant, bluff-forming calcilutite, with *Cryptophragmus* and *Strophomena* locally abundant	36	83
Cross-laminated and wavy-laminated calcarenite and calcisiltite in cliff face	8	47
Metabentonite-clay, also exposed at lane to second house to north, lying on silicified dark surface	1	39
Light-weathering, well-bedded calcilutite with interbeds of limestone-pebble conglomerate; chert in upper part; lower beds and contact exposed in stream to north	38	38
Benbolt formation:		
Laminated and finely ripple-marked, cross-laminated quartz and calcite fine sandstone	21	117
Dark, somewhat siliceous calcarenite and calcisiltite, much in heavy ledges; some beds very fossiliferous, with sponges, bryozoans, and brachiopods; lowest exposures by old roadway north of house; base not exposed	96	96
Peery formation:		
Not exposed; dark, quartz-silty calcisiltite in exposures east of road 2.1 miles south of Union Chapel; about	10	10

TABLE 10.—*Continued*

	Thickness of unit	To base of formation
Bolarian Series		
Ward Cove formation:		
Concealed upper part exposed with Peery south of Union Chapel; probably quartz-silty argillaceous calcitite; about	40	60
Dark, gray-weathering, well-bedded argillaceous calcisiltite, having black chert nodules, and *Gonioceras* and other cephalopods; exposed above cut north of house .3 mile north of Bluegrass; *Sowerbyella* and small rod-shaped bryozoans abundant and weathering from base at south end of cut	13	20
Dark, heavy ledge of black-chert-nodule-bearing argillaceous calcisiltite; exposed in upper part of south end of road cut; probably same as *Nidulites*-bearing basal bed south of Union Chapel	7	7
Disconformity		
Chazyan Series		
Lincolnshire formation:		
Dark, heavy-ledged calcarenite with abundant lenses and masses of black chert; silicified fossils, particularly bryozoans, frequent in road cuts; base below road by stream	48	48
Contact not exposed		
Lurich formation:		
Dark, white-weathering Five Oaks calcilutite; excellently exposed below road at section south of Union Chapel		

County, West Virginia, are continuous into the Five Oaks, and synchronous to a degree, but the first appearance downward of black chert is probably not at a constant chronologic plane, nor are the uppermost dolomites approximately synchronous in all sections. It seems best to refer the whole to a single unit, the Lurich formation. The upper contact is a disconformity, succeeded by Lincolnshire limestone in most sections, but by younger beds in a few sections and in Pennsylvania.

The best measured sections are illustrated in Figure 2. The Narrows section (Table 1) has the Blackford, Elway, and Five Oaks, which constitute the Lurich group in that area. The greatest development of terrigenous siltstone and conglomerate was seen in the hill north of the junction of the Hanging Rock road to Waiteville, 3 miles southwest of Gap Mills, Monroe County, West Virginia (Table 2). Chert pebbles abound in reddish siltstones and dolomite for 100 feet; they seem to disappear along the strike, though exposures are too poor to demonstrate whether through overlap on a disconformity. In eastern Sinking Creek Cove to the south, limestone interbeds near the base of the Lurich have several genera of gastropods, and the uppermost beds have occasional corals.

Chert-pebble conglomerate on Canadian dolomite is excellently exposed for 4 feet in a road cut on U.S. Highway 220 between Falling Spring Church and the Bath-Alleghany County line in southern Warm Springs Cove; an interrupted section of the succeeding dolomite and chert-pebble conglomerate crops out along a lane to the northwest. The upper part of the section is very well exposed in the bluff back of Healing Springs Post Office, and a middle part in the quarry east of the golf course north of the Homestead in Hot Springs.

A mile northeast of Bolar in Highland County 300 feet of Lurich succeeds the cephalopod-bearing Canadian dolomites; it begins with chert-pebble conglomerate, is overlain by silty dolomite, and the upper half has black chert-bearing calcitite below 90 feet of relatively pure calcilutite (Fig. 2).

Tetradium sp. cf. *T. syringoporoides* Ulrich has been observed in several sections; in Highland County it is associated with gastropods in the upper 90 feet of calcilutite 2 miles south of Union Chapel, north of Hightown, and is found about 180 feet from the top in cherty beds a mile northeast of Bolar. Ostracodes have been seen in these and other sections. The northernmost exposures are of the upper calcilutite, in the core of the Germany Cove anticline, east of Key; a small quarry penetrates its contact with succeeding darker less pure Lincolnshire limestone.

Lincolnshire Limestone

The calcilutite (Five Oaks-Clover) at the top of the Lurich is succeeded abruptly by darker,

relatively impure limestone, generally calcarenite containing irregular large masses of black chert. The upper limit of this division is not so obvious, for there is considerable variation within the strata succeeding the Five Oaks calcilutite. Commonly Lincolnshire dark calcarenites with irregular chert masses contrast with Ward Cove less resistant, more argillaceous, finer calcilutites, bearing small black chert nodules and the sponge *Nidulites*; but in some sections the upper part of the Lincolnshire is biostromal, of "reefy" coralline rocks with crosscutting masses of calcarenite and lenses of calcilutite. The interval from the Lurich calcilutite to the *Nidulites*-bearing Ward Cove argillaceous calcilutite has *Sowerbyites* sp. in the more southwesterly sections. The unit is lithically and faunally similar to the Lincolnshire limestone (Cooper and Prouty, 1943) that succeeds the Five Oaks calcilutite in southwestern Virginia. Thus it is classified as the Lincolnshire limestone formation. The writer's isopach map (Kay, 1948, p. 1406) would be little altered by the additional data. Sections are shown in Figure 3.

The basal Lincolnshire not only contrasts markedly in color and texture with the Lurich, but some localities show penetration of up to a foot of the upper unit into the lower, such as just north of the hairpin curve west of the

TABLE 11.—SECTION NEAR KEY AND HARPERS GAP, PENDLETON COUNTY, WEST VIRGINIA

Salona formation from hillside 1.2 miles east-southeast of junction east of Harpers Gap; upper Onego in road cut 1.2 miles south-southeast of Key; older strata on hillside directly above and west of Key; entire section quite well displayed also along road .5 mile south of Harpers Gap junction. Thicknesses in feet.

	Thickness of unit	To base of formation
Trentonian Series		
Salona formation		
Black, buff-weathering argillaceous calcisiltite with interbeds of black silty argillite; occasional fossiliferous beds; *Cryptolithus*, *Dinorthis*, and *Sowerbyella* frequent; .5-foot metabentonite clay about 100 feet in section along road south of Harpers Gap		
Metabentonite, white, lying on chertified calcitite	1	55
Black, buff-weathering calcargillutite in plane-bedded ledges; *Brongniartella* and *Cryptolithus* in loose blocks at top, possibly from above	53	54
Metabentonite, gray-buff	1.5	1
Onega ("Oranda") member, Salona formation:		
Interbedded shaly thin beds of argillaceous calcitite, calcisiltite with small borings, and calcarenite with *Leptaena*, *Oxoplecia*, *Hesperorthis*, *Reuschella*, "*Dalmanella*", and *Sowerbyella*	11.5	32
Metabentonite, buff	.5	21
Interbedded shales, calcarenites, and other calcitites with *Hesperorthis*, *Sowerbyella*, and "*Dalmanella*"; about	20	20
Nealmont formation:		
Calcitite, thin-bedded, quite sparsely fossiliferous	64	207
Calcitite, similar, with some black chert nodules	12	143
Calcitite, similar, with interbeds having rodlike structures weathering to holes, *Camarocladia*	44	131
Metabentonite (N-1), poorly exposed in covered gap in exposure, having underlying silicified surface with *Hesperorthis*	1	87
Calcitite, thin beds of argillaceous calcisiltite, less resistant at base than the underlying rocks, and containing *Sowerbyella* in the very basal bed	86	86
Disconformity		
Bolarian Series		
McGraw ("Stover") formation:		
Heavy ledges of thin-bedded calcisiltite and thin calcarenite lenses; *Camarocladia* bearing; *Cryptophragmus* abundant at top; extending almost to base of good exposure above hill slope	25	25
McGlone ("Snyder") formation:		
Poorly exposed with underlying beds to the road; Ward Cove black calcargillisiltite exposed in hill just east of Key post office; exposed at roadside at Key; McGlone excellently shown in deep ravine 1 mile east of Harpers Gap junction.		

Fish Hatchery at the east end of Sinking Creek Cove, and along the road a quarter of a mile west of the quarry northeast of Falling Spring the basal calcarenite penetrates the Five Oaks calcilutite about a foot. Exposures are almost continuous in the fields half a mile to the east.

TABLE 12.—SECTION ALONG STATE HIGHWAY 869 NORTHWEST OF LOYSBURG, PENNSYLVANIA
(In feet)

	Thickness of unit	To base of formation
Trentonian Series		
Nealmont formation:		
Argillaceous shaly calcisiltite in 2- to 4-inch beds with few coquinal interbeds with *Strophomena* and *Sowerbyella*; *Doleroides* (?) in basal foot overlying heavier-ledged Stover limestone at east end of quarry north of road 100 yards west of junction with Highway 36		
Disconformity		
Bolarian Series		
Stover formation:		
Heavy ledges of dark calcisiltite weathering with dark anastomosing sections of *Camarocladia*; interbedded lenses of calcarenite; *Girvanella* abundant near base; exposed in eastern end of quarry north of road and forming east wall of quarry south of road and creek	34	34
Snyder formation:		
Dark, well-bedded calcisiltite and calcarenite with abundant limestone-pebble conglomerate; *Tetradium cellulosum* in basal and uppermost beds; calcilutite dominant in lower 32 feet, forming principal face of north quarry	52	52
Hatter formation:		
Hostler member:		
Dark, impure, quartz-silty calcisiltite with interbeds of calcarenite; richly fossiliferous, best exposed along east side of Highway 36 just south of Waterside (*see* Kay, 1944, p. 8); measured south of Highway 869 west of bridge	32	89
Grazier member:		
Dark calcisiltite, rather heavy-ledged, with small branching tubular structures weathering to form holes, or *Camarocladia*-like, but smaller than those in road cut west of bridge, with beds below	25	57
Eyer member:		
Very dark-gray, shaly argillaceous quartz siltstone, slightly calcareous, having few fossils—*Multicostella* and *Illaenus*	32	32
Disconformity		
Chazyan Series		
Loysburg formation:		
Clover member:		
Well-bedded impure calcilutite passing down into dolomite beds		

at the south end of Warm Springs Cove. The irregularity is due to erosion; there is no accumulation of residue from solution along the contact, and in places the basal beds of the Lincolnshire calcarenite contain pebbles of white calcilutite. Invariably there is an abrupt lithic change.

The greatest measured and computed thickness along the northwestern outcrops is in the southern part of Warm Springs Cove in a section of 140 feet that also exhibits the range of lithologic features. The lower beds—dark, black-chert-bearing, bedded calcarenites—show best in the quarry south of the Sinking Spring Church near the county line on Highway 220; The upper beds, about 70 feet of calcarenite with biostromes of the coral *Billingsarea*, bryozoans, and algae, show extensively in the open fields beyond the farm house on the lane from the church toward McGraw Gap road (Pl. 1, fig. 2). The organic masses have patches of calcilutite and are channeled by coarse calcarenite.

The reef facies is not persistent. Half a mile to the north, reefs are infrequent, calcarenite beds preponderant. The succeeding Ward Cove is well-bedded argillaceous calcisiltite having small globular elliptical nodules of black chert and frequent *Nidulites*. Biostromal beds are absent in the upper Lincolnshire in a section

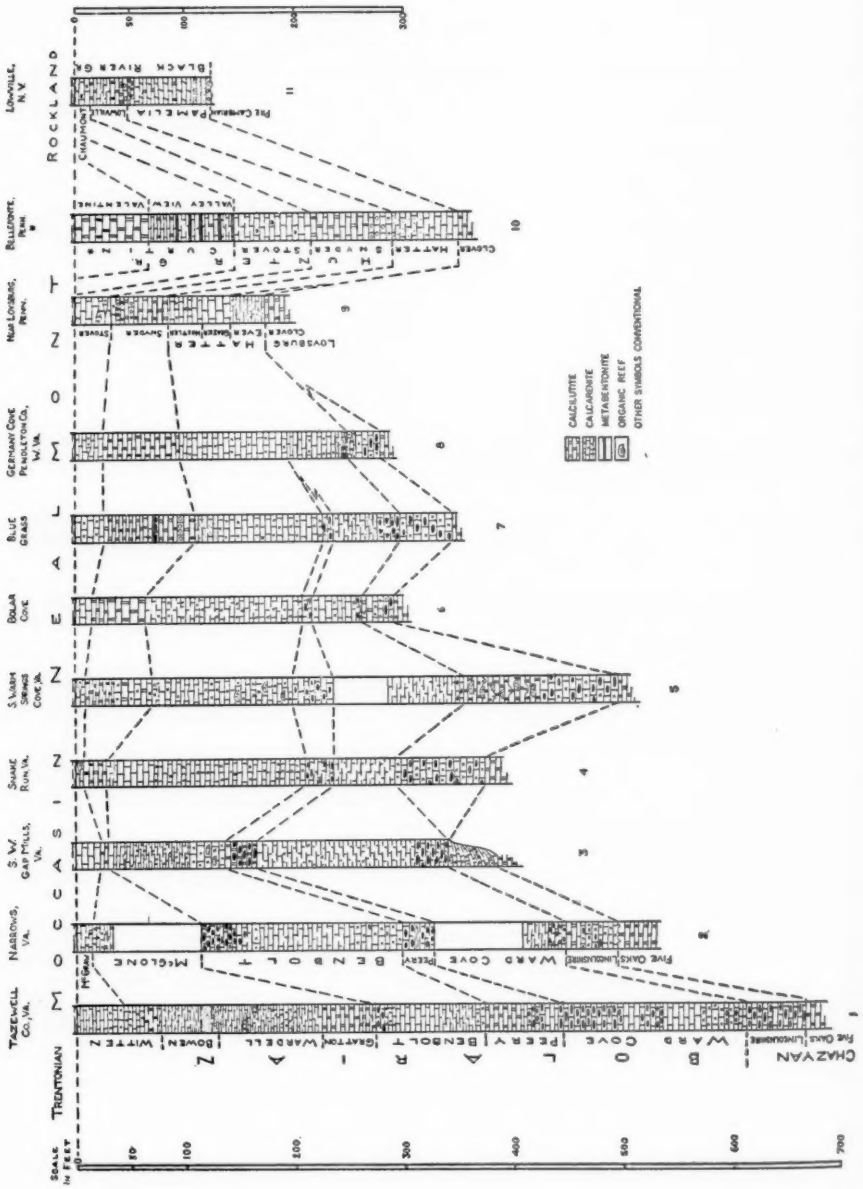
about .3 mile west of the highway north of the lane about half a mile south of the county line, and the contact of granular, well-bedded cherty Lincolnshire with the thinner-bedded noncherty Ward Cove argillaceous calcisiltite is not readily apparent. In a belt southwest of Gap Mills, Monroe County, West Virginia, the top of the Lincolnshire consists of coralline beds and associated calcilutite locally overlapped by Ward Cove. Just west of the Hanging Rock road south of the junction 3 miles southwest of Gap Mills, it consists of 60 feet of dark, crystalline, black chert-bearing limestone, separable with difficulty from the succeeding Ward Cove. Half a mile east, the upper part is irregularly bedded, biostromal, with the coral *Billingsarea* frequent. In another half mile on the slope south of a sink, the chert nodule-bearing basal Ward Cove argillaceous calcitite lies directly on the Five Oaks; this is the only locality in the Western Anticlines in the Virginias in which the writer has found no Lincolnshire.

At McGlone, in an anticlinal core in Turkey Cove, a few miles northwest and beyond the St. Clair fault, the basal Lincolnshire cherty, *Sowerbyites*-bearing calcisiltite is well exposed on Five Oaks calcilutite; succeeding cherty calcitites give a total of 30 or 40 feet. Along the Virginian Railroad, east of the New River at The Narrows, 20 miles farther west and south of the same fault, 40 feet of calcisiltite on the Five Oaks grades into rather pure, laminated calcilutite in the upper few feet; chert is sparse and limited to the base which has the calcilutite pebbles in conglomerates. The succeeding Ward Cove calcarenite penetrates in a narrow channel into the Lincolnshire calcilutite, cutting stylolite partings in the latter.

In Richpatch, about 10 miles southeast of Warm Springs Cove, the Lincolnshire is exposed in many localities, seemingly best along Raleigh Creek near the northeast gap, where 110 feet was measured and computed, much of it black chert-bearing calcarenite and calcisiltite. The lower beds with abundant *Pachydictya robusta* Ulrich and masses of black chert are excellently exposed in a narrow ravine west of the stream at the Five Oaks calcilutite contact; higher beds, with *Sowerbyites triseptatus* (Willard), are also displayed in ledges east of the Creek just south of a culvert near the contact with thinner-bedded Ward Cove argillaceous calcisiltite having black chert nodules and *Nidulites*. In Snake Run Cove to the west and north, a thickness of 115 feet was determined about a mile east of Iron Spring junction; the contact with the Ward Cove is just south of a sharp curve around a small ravine east of a farm house above the road. In Back Valley, Virginia, south of Paint Bank, interrupted exposure of 85 feet of Lincolnshire is above well-exposed Five Oaks calcilutite along the Highway about a mile west of the Paint Bank water gap. To the south, in eastern Sinking Creek Cove, about 125 feet overlies the Five Oaks calcilutite exposures along the roadside west of the Fish Hatchery. The upper, heavy-ledged calcarenites are somewhat biostromal and are succeeded by rather shaly Ward Cove with *Nidulites* and *Echinosphaerites*.

The Lincolnshire generally is thinner north of the Warm Springs Cove sections. On the hillside west of the road 2 miles north of Bolar, on the Alleghany-Bath county line, 55 feet of rather pure calcarenite with black chert irregularly distributed in the lower half, and a little calcilutite lensing in and out at the top, is exposed in contact with less resistant and poorly exposed *Sowerbyella*-bearing shaly Ward Cove. Across the Valley and a little to the south, Lincolnshire, above an excellent Loysburg section, has abundant *Pachydictya robusta* as well as occasional *Gonioceras* sp. in finer-textured, more siliceous rock.

Along the Bluegrass-Germany anticline to the west and north, good sections are scarce. About 60 feet, heavy-ledged and cherty, forms the core of the anticline along a stream east of the secondary road a mile south of its junction with State Highway 89, east of Mill Gap water gap; the succeeding Ward Cove has quartz-silty shales near the base, with some black chert nodules. The same contact is better exposed above 47 feet of Lincolnshire, nearly 10 miles north, just east of the road, about 2 miles south of Union Chapel. Twelve feet of basal Ward Cove chert-nodule and *Nidulites*-bearing calcitite intervenes between the granular, cherty Lincolnshire exposed in a road cut and black quartz-silty argillaceous rock exposed just east of the roadside fence on the north side of a vale. In road cuts north of Bluegrass,


ROCKLAND
CHAZYAN
TRENTONIAN
MOHAWKIAN
CINCINNATIAN
WARD COVE
PEERY
BENBOLT
WARDELL
BOWEN
WITTEN
MCGLONE
BENBOLT
WARD COVE
PEERY
FIVE OAKS LIMESTONE
BLACK RIVER GR.
CHAUMONT
PAMELIA
VALLEY VIEW
VALENTINE
HATTER
CLOVER
LOYSBURG
CALCILUTITE
CALCARENITE
METABENTONITE
ORGANIC REEF
OTHER SYMBOLS CONVENTIONAL
SCALE IN FEET
Tazewell Co., Va.
Narrows, Va.
S. W. Gap Mills, Va.
Shane Run, Va.
S. Walsh Spring Cove, Va.
Bolar Cove
Blue Grass
Gerhart Cove Pendleton Co., W. Va.
New Loysburg, Penn.
Bellefonte, Penn.
Lowville, N.Y.

49 feet of cherty and fossiliferous Lincolnshire is in contact with Loysburg calcilutite exposed along the stream wall below; the highest ledges in the cut are a foot or so of more shaly, argillaceous Ward Cove calcisiltite having abundant *Sowerbyella* and bryozoans that weather free. The Lincolnshire has silicified fossils on its weathered surfaces, particularly *Pachydictya robusta*, *Mesotrypa* sp., and *Mimella* sp.; *Sowerbyites* was not seen.

The northernmost exposures are directly east of Key in Germany Cove. The upper Lurich calcilutite in the quarry is overlain by cherty calcarenite succeeded along the stream by gray calcarenite containing calcite fossils; the rock is not so recrystallized as in most exposures and is chert free. The upper contact is not exposed, but the basal Ward Cove black shaly argillaceous and siliceous calcisiltite with frequent *Strophomena* and *Sowerbyella* and a few black chert lenses is at the base of the bluff that the stream skirts. The Lincolnshire is about 30 feet in this section.

The long interval to Central Pennsylvania includes the point of disappearance of the Lincolnshire, for, near Bedford and Loysburg, shaly calcareous quartz siltstone of the Eyer member of the Hatter formation, much like the basal Ward Cove of Germany Cove, lies directly on Clover calcilutite of the Loysburg formation (Table 12).

Fossils: The Lincolnshire is ordinarily sparsely fossiliferous, but occasional coquinal beds are present, and nearly any section shows a few organisms. Silicification is common, so the fossils can be etched from the calcitite. *Pachydictya* sp. cf. *P. robusta* Ulrich, a bryozoan having broad, varyingly rippled fronds with small maculae, is generally present. *Sowerbyites triseptatus* (Willard) has been observed in sections near Gap Mills and in Richpatch; species of *Mimella* are widespread but not common; *Multicostella* has been collected in most faunules. The upper biostromal beds, particularly well displayed in the hills toward McGraw Gap in the southern Warm Springs Cove, are characterized by corals such as *Billingsarea* and, in calcilutite masses within the organic structures, shingled moults of the trilobite *Basiliella* sp. A species of *Gonioceras* was seen near McGraw Gap and along the east side of Bolar Cove.

Silicified trilobites were found in residues from the Lincolnshire in the Appalachian Valley (Whittington and Evitt, 1953), but none was seen in the samples leached from the Western Anticlines, though many of the brachiopods and bryozoans are sliicified in these areas.

Bolarian Series

General Statement

The rocks above the Lincolnshire have been defined as the Ward Cove, Peery, Benbolt, Gratton, and Witten formations in southwestern Virginia (Cooper and Prouty, 1943). Within the Western Anticlines, the southwestern sections are contiguous to those of southwestern Virginia; the northeastern sections are very similar to those in the sequence in south-

Figure 3.—Sections of Bolarian Formations and Lincolnshire

1. Tazewell County, Virginia, principally from Cooper and Prouty (1943), with revision of upper beds exposed near Scales.
2. Narrows, Giles County, Virginia, along Virginian Railway east of New River North of Narrows.
3. Southwest of Gap Mills, Monroe County, West Virginia, from exposures along and east of Hanging Rock Road south of road junction 3 miles southwest of Gap Mills.
4. Snake Run, Alleghany County, Virginia, from exposures on slope south of road half a mile east of Iron Spring junction.
5. McGraw Gap, Alleghany County, Virginia, from exposures east of house on lane southeast of Sinking Spring Church, below road to McGraw Gap and Clifton Forge.
6. Bolar, from exposures west of road 2 miles north of the village in Highland County, Virginia.
7. Bluegrass, Highland County, Virginia, from hill slope north of the village.
8. Germany Cove, Pendleton County, West Virginia, from exposures along ravine about a mile east of Harpers Gap, and ravine from Seneca Caverns to Key.
9. Loysburg, Bedford County, Pennsylvania, from roadside quarries 1 mile north of Bedford on Highway 869.
10. Bellefonte, Centre County, Pennsylvania, from Bell Mine, American Lime and Stone Company; after Kay (1943; 1944). The Curtin is a facies of the Trentonian Nealmont limestone (Morris Rones, Personal communication).
11. Lowville, Lewis County, New York, along Mill Creek; after Young (1943).

ern Pennsylvania, where the Hatter formation has been divided into the Eyer, Grazier, and Hostler members, and the Hunter group into the Snyder, Stover, and Curtin formation (Kay, 1943; 1948). The Lincolnshire is thought to be Chazyan; the Moccasin and Nealmont formations that overlied the Witten are classed as Trentonian. Recent studies by Morris Rones indicate that the Curtin limestone in Pennsylvania is actually a phase of the Nealmont limestone, a facies of the Oak Hall member of the Nealmont. The rocks between the Lincolnshire and the Nealmont have been defined as the Bolarian Series (Kay, 1947; 1948) named for Bolar Cove (Pl. 1, fig. 1) in the area of this study.

Whether the Bolarian is a series, subseries, or stage depends on the conception of each term, as well as on the demand for categories in classification. The term Blackriverian has been used recently for a "stage" of the Ordovician (Moore, 1949, p. 118; Bassler, 1950, p. 10). In New York Black River has long been used as a group or formation name. In Ontario and Michigan the "Black River" has commonly included lower Trentonian strata. The writer considers the Black River Group of New York to be Bolarian, but the Bolarian of the Western Anticlines to include beds older and possibly younger than that group, to be more representative of the time between Chazyan and Trentonian, as well as having more fossiliferous facies.

The writer uses Ward Cove, Peery, and Benbolt in his sections. In the Virginias it is proposed that the new name McGlone be applied to the succeeding rocks thought to be like the Snyder of Pennsylvania and the new name McGraw to those similar to the Stover. Extension of the Pennsylvania names (Kay, 1948) has been criticized because of doubt that the correlation is correct (Woodward, 1951, p. 206). The McGlone includes at the top the *Cryptophragmus* zone of the Witten formation of the Narrows (Table 1; Cooper, 1944b, p. 24).

Thus, the Bolarian Series in the area comprises the Ward Cove, Peery, Benbolt, McGlone, and McGraw formations.

Ward Cove Limestone

Definition: The Lincolnshire formation in sections south and west of Highland County is overlain by thin beds of argillaceous calcilutite bearing black chert nodules; *Nidulites* is sparingly present. In Highland County, as 2 miles north of Bolar, a mile south of Millgap post office, and half a mile north of Bluegrass, the beds succeeding the Lincolnshire are a few feet of *Sowerbyella*-bearing calcareous argillite; about 13 feet of *Nidulites*-bearing dark argillaceous calcitite overlies Lincolnshire in an intermediate section 2 miles south of Union Chapel, north of Hightown. Throughout the region, the succeeding calcareous beds are only sparsely cherty.

A persistent black chert-bearing zone 40 feet or so thick (Pl. 1, fig. 3) is more than 200 feet from the Lincolnshire at Sinking Creek and Richpatch coves. It simulates the lower part of the Peery (B. N. Cooper and Prouty, 1943) limestone west of the New River by its stratigraphic position and the presence of the pteropod *Polylopia*. Thus, the underlying beds have the position of the Ward Cove formation (B. N. Cooper and Prouty, 1943).

A similar, thinning chert zone continues northward above a decreasing interval until it is but a few feet thick, 50 feet above the Lincolnshire in Highland County in both Bolar and Bluegrass coves. Though the beds above the Lincolnshire in Germany Cove are lithically like the *Sowerbyella* beds near Bluegrass, the chert zone of the Peery was not recognized east of Key. A thin unit of dark siliceous and argillaceous siltstone in Bedford County, Pennsylvania, the Eyer member, lies directly on the Loysburg and resembles the attenuate Ward Cove and Peery of Pendleton County. Northeastward in Pennsylvania, still younger beds overlie the Loysburg. Because the thicker sections in the Virginias are virtually continuous with the type development of the Ward Cove formation west of the New River, and because the Eyer probably represents but an attenuate upper part of the Ward Cove, the latter name is adopted for rocks succeeding the Lincolnshire and overlain by the cherty Peery in the Western Anticlines.

Lithology: The Ward Cove formation is dominantly argillaceous calcitite or calcareous argillite. Most workers call it limestone but it has such a large proportion of insoluble argillaceous clay in many beds that the residue from a leached slab remains consolidated.

Throughout its exposure, arenites are relatively rare, and quartz silt is infrequent. Black chert nodules are generally restricted to the base, and chert-bearing rocks at the top are referred to the Peery. The sections can be separated readily into those thicker and thinner than 100 feet, the latter restricted to Snake Run, Bolar, and Bluegrass-Germany Valley coves.

Along Raleigh Creek in northeastern Richpatch, 240 feet of Ward Cove is excellently exposed from the top of the Lincolnshire by the culvert where the stream crosses the road to the cherty Peery exposures near the northern end of the high cliff by the spring (Table 4). The beds are also seen to advantage in somewhat interrupted exposures on the ridge west of the Eagle Rock road out of the southeastern part of the cove; thickness was calculated as 253 feet, and excellently shown Peery cherty limestons contains *Polylopia*. In these, as in other thicker sections, chert nodule-bearing bedded argillaceous calcilutite in the lower part has frequent *Nidulites*, and higher more massive argillaceous rocks have abundant *Sowerbyella* sp. cf. *S. negrita* (Willard); a similar sequence is ascribed to the typical Ward Cove of southwestern Virginia (Cooper and Prouty, 1943, p. 829). The two genera are not limited to the lower and upper parts of the formation, respectively. Sections in the several other outcrop areas are summarized in the sections and in Figure 3; they have poorer and less continuous exposure. At one locality, about 2 miles southwest of Gap Mills, the Ward Cove lies directly on Five Oaks calcilutite.

The thinner sections are present in the outcrop belts in Bolar Cove and along the Bluegrass-Germany anticline. In an interrupted 50-foot section on the hill west of the road 2.1 miles north of Bolar, the Peery barely crops out low on the south hillside. The lowest Ward Cove beds are dark, dense, shaly argillaceous calcitites with a few chert nodules; *Sowerbyella* becomes abundant within 3 feet of the base as the beds become more shaly and noncherty. Exposure is interrupted in similar beds with some calcisiltite and calcarenite interbeds extending to the base of the 8 feet of cherty Peery. In northern Bluegrass cove an excellent section along a ravine 2 miles south-southwest of Union Chapel (and half a mile from benchmark 2055 feet) shows 13.5 feet of cherty *Nidulites*-bearing heavy-ledged Ward Cove calcitite at the fence on the east side of the road, 10 feet of siliceous silty argillite, 10 feet of black chert nodule-bearing argillaceous calcilutite, and 20 feet of *Girvanella-*, *Multicostella-*, and bryozoan-bearing calcarenite. The formation is similar in the southern end of the same anticlinal cove, where the best section is along a ravine east of the Mill Gap to Valley Center road about half a mile south of the junction with the main highway; about 6 feet of basal cherty Ward Cove is succeeded by quartz-silty argillaceous beds. Northward in the Germany Valley cove, the basal Ward Cove east of Key is calcareous, quartz-silty argillaceous shale with a little chert and pyrite, bearing *Multicostella* sp. and *Sowerbyella* sp.; the Peery was not recognized in the succeeding section.

The Ward Cove thus thins northwestward from a maximum of more than 250 feet to 50 feet or less (Fig. 4). There is no suggestion of erosion of the top of the Lincolnshire or of conglomerate at the base of the Ward Cove. Nevertheless, the contact is probably one of regional overlap. The Ward Cove seems separable into a lower, cherty, *Nidulites*-bearing member and an upper, more argillaceous, *Sowerbyella*-rich unit; as this combination persists into southwestern Virginia, the units are probably time stratigraphic. The alternative is that the lower is a deeper-water facies, and the upper a shallower one, but there is no suggestion of intertonguing. The Peery cherty zone is also time stratigraphic.

The lower Ward Cove thins from the more than 200-foot range of *Nidulites* in Richpatch to virtual absence in Germany Valley; the thinning is by overlap on a slightly eroded surface of the Lincolnshire. The upper Ward Cove thins from about 100 feet to 50 in northern sections; this is by convergence, which may also account for part of the thinning of the lower Ward Cove.

The upper beds are lithically similar to the Eyer member of the Hatter formation in southern Pennsylvania (Kay, 1944), which is overlapped northeastward in central Pennsylvania. Thus, along this line of section of some 200 miles from southern West Virginia to central Pennsylvania, the Lincolnshire and the Ward Cove progressively disappear by onlap

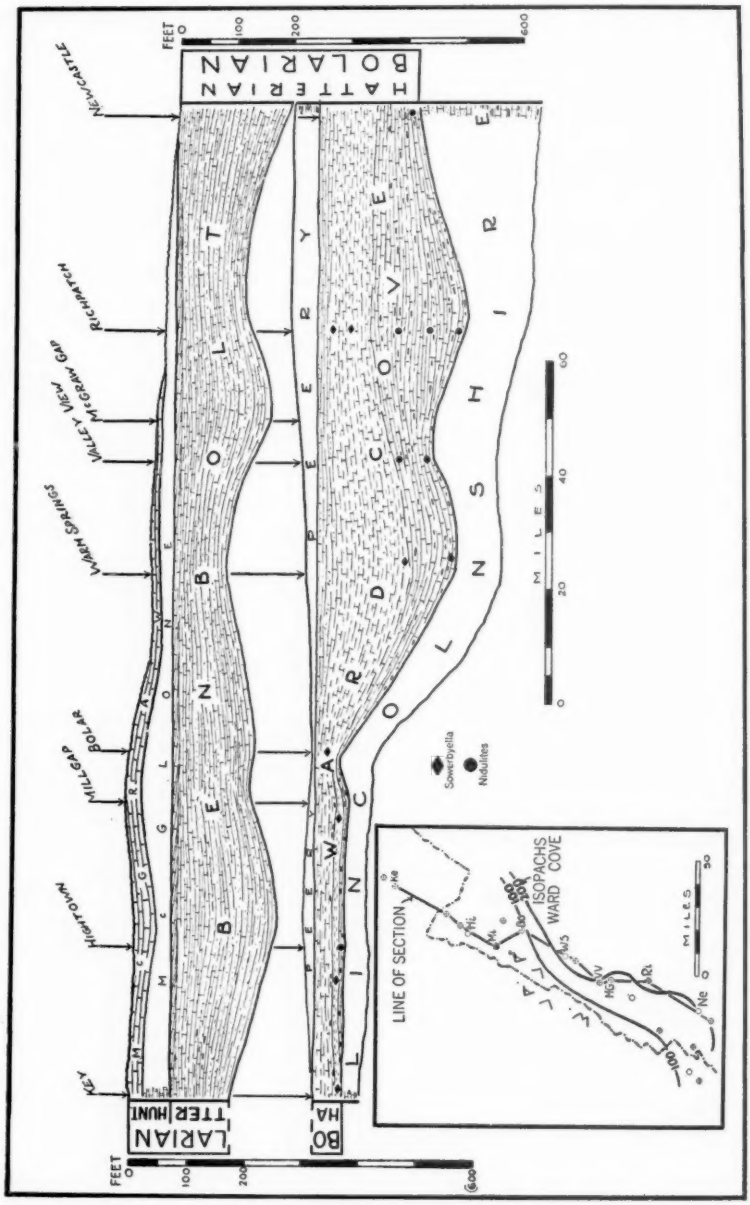


FIGURE 4.—RESTORED SECTION OF BOLARIAN FORMATIONS

over the Five Oaks and equivalent Clover calcilutites. This two-dimensional relationship may not give a true presentation of the three-dimensional form. The data suggest that the thicker sections lie southeast of a zone of flexure that cuts across the belt of outcrop obliquely, the trend more westerly than that of present structure (Figs. 3, 4).

Peery Limestone

The zone of black-chert-bearing quartz-silty limestone above the chert-barren *Sowerbyella* and somewhat cherty *Nidulites* argillaceous calcitites of the Ward Cove has been classed as Peery (Cooper and Prouty, 1943), a unit originally a member of the Cliffield formation. The Peery does not have the twofold division described for its type region but has the black cherty lithology of the lower member and the pteropod *Polylopia*.

The rocks classed as Peery are characterized best by their black chert nodules (Pl. 1, fig. 3), but the associated calcitite is distinctive. The beds are quite argillaceous and weather with dark, quartz-silty surfaces that bound lighter, less silty calcitite so that the whole has a rather reticulated pattern of shaded surface. The cherty zone diminishes from 40 feet in easternmost Sinking Creek Cove, at the base of the cliff just east of the Fish Hatchery, and nearly 50 feet on the far slope of the ridge west of the Eagle Rock road gap from Richpatch Cove, to 18 feet on the hill south of the private lane from Highway 220 north of Mitchelltown toward Duane Gap, northern Warm Springs Cove, to 5 feet or so on the hill 2 miles north of Bolar, and to similar or smaller thickness to the north and west in Bluegrass Cove (Figs. 3, 4). Chert was not seen in the beds 50 feet or so above the Lincolnshire in Pendleton County, West Virginia.

Polylopia is present in the cherty Peery in the southeast Richpatch and Hanging Rock sections (Tables 4, 2), and behind Mitchelltown School, Warm Springs Cove. A fine-textured fenestrate bryozoan, *Subretepora*, is abundant at the Fish Hatchery exposure in Sinking Creek Cove.

Benbolt Limestone

The cherty Peery limestone is succeeded by quite impure calcitite of variable composition and texture, commonly terminating with a few feet of finely cross-laminated calcareous quartz siltstone. The overlying rocks are rather pure plane-laminated calcitite. The cross-laminated zone is sufficiently persistent to form a convenient and distinctive upper boundary to a stratigraphic unit, but is not assumed to be synchronous. A similar zone terminates the Benbolt formation above the Peery in Tazewell County (Cooper and Prouty, 1943).

The formation was not recognized as separable into persistent members, though it has varied lithologies. In most places it is somewhat argillaceous and siliceous calcisiltite having undulating partings giving a reticulate pattern of bedding surfaces in section, and producing rather cobbly weathering. Coarser-textured phases, calcarenites, are occasionally cross-laminated. In many places the formation is biostromal, having masses of trepostome bryozoans—as in the section near McGraw Gap and that east of Trimble—or smaller coralla of *Tetradium* aff. *T. gracile* Bassler and *Foerstephyllum* sp. aff. *F. halli*, (Nicholson)—as in the quarried cliff directly east of Hanging Rock road 3 miles southwest of Gap Mills. In some localities *Dystactospongia* is common, as half a mile east of the chapel junction in western Richpatch; a mile south of Millgap, north of Bluegrass and by Seneca Caverns, *Receptaculites* is common.

The Benbolt ranges from 170 feet or more (Snake Run and Sinking Creek Hatchery) to about 100 feet (Seneca Cavern, Germany Cove and Dunne Gap, Warm Springs Cove). The thicknesses seem a little greater along a medial trend than in Richpatch and Back Valley to the southeast or in Bluegrass-Germany coves in the northwest.

The upper contact of the Benbolt is less definite than the lower. Biostromal calcarenite and quartz-silty calcilutite characterize the Benbolt, and pure calcilutites the McGlone. The contrast is gradational, so that placement of the contact in different sections is only approximately time stratigraphic.

Fossils are rare or absent in much of the formation. Many biostromal beds contain *Foerstephyllum* and *Tetradium gracile* Bassler, *Dystactospongia*, and massive bryozoans. *Multicostella* is seen occasionally in calcisiltites, and bryozoans such as *Subretepora* in upper beds.

The Benbolt is well exposed along the Virginian Railroad below Narrows, where the upper beds have some black chert in calcisiltite beds (Table 1). There is interrupted exposure in the fields along Hanging Rock Road southwest of Gap Mills, West Virginia, and a quarry has been opened in the upper beds. *Polylopia*-bearing Peery is best seen in the ravine to the east (Table 2). The Benbolt is fully exposed in the hillside north of Virginia Highway 311 northeast of the Five Oaks exposure along the roadside in Back Valley Cove south of Paint Bank, Craig County, and by the Fish Hatchery at the east end of Sinking Creek Cove. In these sections, as well as in that at southeast Richpatch Cove in the ridge west of the Eagle Rock Road, the Benbolt approaches the Trentonian, which at the Fish Hatchery has quartz sandstone at the base.

The Benbolt is exposed at intervals east of Iron Hill in Snake Run Cove (Table 3), and excellently as the "McGraw Gap" section (Table 5), in southern Warm Springs Cove about 3 miles northwest of McGraw Gap. Exposure is almost complete by Mitchelltown School to the north in the same cove, and interrupted in the hill southeast of Dunne Gap. Other exposures are sparse. The sections along the mountain road at the county line east of Bolar (Table 7) and 2 miles north of the hamlet are interrupted. The beds crop out in the core of the same Bolar anticline half a mile south of Trimble, but only the upper beds are well shown (Table 8). There are many exposures but few good sections in the Bluegrass and Germany coves. The upper beds are extensively shown in the core of the anticline about a mile southeast of Mill Gap, east of the road to Lower Gap. There is interrupted exposure of the formation in the hills northeast of Bluegrass in the north end of the cove (Table 10). In Germany cove, exposures are extensive along the roadside south of Key, as well as just east of Seneca Caverns (Woodward, 1951, Pl. XXI, p. 223).

Hatter Formation

The Hatter formation (Kay, 1941) consists of the Eyer, Grazier, and Hostler members (Kay, 1943) in central and southern Pennsylvania. The Eyer member is restricted to the southwestern areas of exposure, and is overlapped by younger beds in northeastern sections (Kay, 1944). The best section known to the writer in the southern counties is that along state road 869 west of its junction with the Waterside-Loysburg road in northern Bedford County, extending from exposures of Loysburg calcilutite (Clover member) south of the stream beyond the bridge to those in the Salona formation at the junction (Table 12). The exposures of the Hatter formation south of the road west of the bridge are lithically like the Ward Cove-Peery-Benbolt beds in Pendleton County. The basal 30 feet is shaly, somewhat calcareous and argillaceous quartz siltstone, weathering with irregular darker patches much as does the Peery, but lacking black chert nodules. Fossils are few; *Multicostella* sp. is abundant in a few layers much as in the beds succeeding the Lincolnshire in northern Pendleton County, West Virginia. The succeeding Grazier member, quartz-silty calcitite with abundant fucoidal structures weathering to form small holes, about 25 feet, and the Hostler member, shaly argillaceous and arenitic calcitite of about 32 feet, richly fossiliferous at near-by Waterside (Kay, 1944, Fig. 6, p. 8), resemble beds in the Benbolt in the Virginias, and have similar faunas. The Snyder calcilutites succeed the Hatter, just as the McGlone calcilutites succeed the Benbolt.

The name Hatter formation can be applied advantageously in Pendleton County, West Virginia, to the rocks between the Lincolnshire and the calcilutite of the McGlone where it is not possible to recognize the Ward Cove, Peery, and Benbolt formations.

McGlone Limestone

Above the siliceous cross-laminated calcisiltite at the top of the Benbolt and below the heavy-ledged, pitted-weathering, brittle, jointed McGraw is well-bedded calcilutite with variable quantities of calcilutite pebble conglomerate and laminated quartzose calcisiltite (Figs. 3, 4) forming the McGlone formation. From Gap Mills southwestward, the upper few feet are calcarenite containing the alga *Cryptophragmus*, a form frequent in the corresponding position northward to Pendleton County. The new name McGlone is from the locality in Turkey Cove, west of Gap Mills, Monroe

County, West Virginia, the beds being exposed along the north flank of the anticline to the east; the type section is defined as below that of the McGraw formation near McGraw Gap, Alleghany County, Virginia (Table 5). The McGlone formation consists of beds referred to as Snyder in Virginia (Kay, 1943); though believed equivalent to the Snyder limestone of Pennsylvania, the name McGlone is adopted.

The McGraw is absent in sections in eastern Sinking Creek, Back Valley, and Richpatch coves, and the basal Nealmont overlies McGlone calcilutite. At Sinking Creek, Back Valley, and in Pendleton County, the contact between the Benbolt and McGlone is not readily apparent because cross-laminated beds are not developed. The top of the McGlone in southwestern sections is the Cryptophragmus zone of the Witten formation, and the McGraw is the lower part of the Camarocladia zone of the Witten as defined by Cooper and Prouty. The Benbolt is separated from the McGraw by the Wardell, Gratton, and lower Witten, occupying the stratigraphic position of the McGlone but several hundred feet thick. The Stover of Pennsylvania reaches nearly 100 feet, whereas the McGlone in the Western Anticlines ranges from 60–70 feet of well-bedded calcilutite in Pendleton and Highland counties to as little as 10 feet at Gap Mills, Monroe County. Probably there are diastems within the McGlone sequences, but their positions and characters have not been recognized. The same *Cryptophragmus*-bearing calcarenite persists below the McGraw *Camarocladia* beds in the thinnest sections.

A 1-foot buff metabentonite on a chertified surface is well exposed in a shallow cut along the lane east of the road three-eighths of a mile north of Bluegrass, Highland County (Table 10). In the cliff section a quarter of a mile north of the town, the same bed lies nearly 40 feet above the top of the Benbolt siliceous calcisiltite. Neither the clay nor the chert was seen elsewhere, but few sections have complete exposure across this interval.

The McGlone rather constantly has the alga *Cryptophragmus antiquatuus* Raymond in calcarenitic beds at the top when the McGraw is preserved above it. *Tetradium* sp. cf. *T. cellulosum* (Hall) is frequent, and occasional coquinas have abundant brachiopods, particularly *Strophomena* sp. As a whole, the unit is sparsely fossiliferous.

McGraw Limestone

The McGraw limestone is the well-bedded but heavy-ledged, brittle, rather pure calcitite weathering with small holes, the most persistent and distinct lithic unit in the sequence above the McGlone. The name is from McGraw Gap, Alleghany County, southeast of Warm Springs Cove; the type section is in the southeast end of the cove (Table 5). The lithology and stratigraphic position resemble the Stover (Kay, 1941; 1943; 1944) limestone of Pennsylvania, with which it is correlated.

The basal contact of the McGraw with the McGlone is invariably sharp, as the McGlone commonly has *Cryptophragmus*-bearing calcarenite, particularly in more southerly sections, or plane-bedded calcilutite. The contrast at the upper contact is even more abrupt; the few feet of succeeding beds is poorly exposed and argillaceous or silty, lying with erosional disconformity on the McGraw. The McGraw tends to support a cliff with a grassed terrace or gentle slope at the base of the succeeding Nealmont.

The McGraw is generally 6-inch to 1-foot ledges of dense, brittle calcitite broken into rectangular joint blocks. Each ledge is irregularly laminated, has frequently thin calcarenite lenses, and commonly has the ramifying cylindrical structures classed as *Camarocladia*, which are less resistant and weather away to leave holes.

The uniformity of lithology is paralleled by a persistence of small thickness. From a maximum of nearly 30 feet in northwestern sections as at McGlone in Mercer County and at localities from Lower Gap to Harpers Gap along the Bluegrass-Germany anticline (Table 11), the unit thins to extinction between the Gap Mills-Snake Run-McGraw Gap sections (Tables 2, 3, 5) and those of Sinking Creek-Back Valley, and Richpatch (Table 4), in which Trentonian sediments lie on the McGlone. Thickness exceeds 40 feet southwestward near Tazewell. In Bedford County, Pennsylvania similar Stover limestone is 30–40 feet thick. The beds thicken to nearly 100 feet in the northwestern sections

in Centre County, central Pennsylvania; they thin to extinction between Friends-Morrison-Kishacoquillas coves and the Blacklog cove in eastern Huntingdon County (Kay, 1943, p. 15).

Though this unit has seemed most distinctive to the writer, the lithic contrast must not be so evident to others, for Woodward (1951) does not recognize the beds as a stratigraphic unit, and Cooper and Prouty (1943) include it as the lower and larger part of the Camarocladia zone. Though part of the southeastern thinning is due to regional bevelling, the progressive decrease, and the similar decrease in the underlying McGlone show that the northwestward tilt of the region was normal and persistent.

The contact of the succeeding beds with the Nealmont is rarely exposed, for the basal Nealmont beds are usually so little resistant that they lie beneath a sod-covered slope just above the well-exposed McGraw. Exposures generally show *Doleroides*[2]-, *Pionodema*[2]-, or *Sowerbyella*-bearing quartz-silty calcareous beds, or calcarenite on an irregular surface of the McGraw; the penetrating irregularities are only an inch or so deep. These can be seen on the hillside north of Bluegrass and just north of the stream a quarter of a mile southeast of Trimble in Highland County, as well as at scattered places as far southwestward as at The Narrows (Pl. 2, fig. 2; Table 1) and in the type of section of the Witten formation southwest of Tazewell (Pl. 2, fig. 1) (Cooper and Prouty, 1943, p. 877). The contact of Nealmont on Loysburg in southern Pennsylvania is well shown in the eastern end of the quarries north of State Highway 869, north of Loysburg (Pl. 2, fig. 3).

The McGraw limestone is sparsely fossiliferous. *Cryptophragmus antiquatus* Raymond is frequent in the northern exposures in Pendleton County, West Virginia.

Trentonian Series

Correlation

In this area the rocks equivalent to the Trentonian formations of New York and Ontario (Kay, 1937) differ from those of the Chazyan and Bolarian in that their facies change very greatly within the region. On the southeast, the distinctive red sediments like those of the Moccasin formation of southwest Virginia are succeeded by the variable Eggleston formation of local definition and the so-called Martinsburg shaly and argillaceous limestone. On the northeast, the sequence has a lower formation like the Nealmont formation of Pennsylvania and an upper formation like the Salona with a distinctive basal member, the Onego. The two divisions of the Salona are very similar to strata above the Edinburg limestone in the western sections in the Shenandoah Valley, and the Oranda formation of that region resembles the Onego member.

Moccasin and Eggleston Formations

Sections from the New River to the Valley near Lexington: The Trentonian sections at The Narrows and near Gap Mills (Tables 1, 2) contain two named units, the Moccasin and Eggleston, overlain by the "Martinsburg" formation. The Moccasin has a four-fold division from Gap Mills to Richpatch, with lower buff and white calcitites, lower reddish calcareous argillites, middle rather pure, white-weathering calcilutites, and upper reddish and buff argillaceous calcitites. The Eggleston has quartz sandstone beds at the base; two thick metabentonites, V-4 and V-6 of Rosenkrans (1936), in The Narrows section divide it into a lower pink and buff and an upper buff argillite with some fossiliferous calcarenites and limestone conglomerate. The succeeding basal "Martinsburg" has a series of thin metabentonites; those 30 feet above the base have been termed "cuneiform" because of the angular blocks of somewhat silicified silty rocks associated with several metabentonites through 10 feet or more.

The definitions of the limits of the Moccasin and Eggleston have varied among authors, and the measurements of the New River section below Narrows (Table 1) have differed somewhat (Woodward, 1951, p. 285, 310). The writer places the base of the Eggleston at a quartz sandstone 17 feet below a thin metabentonite, V-3 of Rosenkrans (1936, p. 92) though the intervening reddish beds are commonly classed as Moccasin. Metabentonite V-4

[2] Specimens of *Doleroides* and of *Pionodema* were identified in the laboratory from each of several localities, but some specimens identified in the field as *Doleroides* may actually have been *Pionodema*.

is 25 feet higher, and V-6, 40 feet above that, is at the top of about 90 feet of Eggleston. Rosenkrans omits the lower reddish beds from the Eggleston but includes 65 feet of succeeding argillaceous limestone, containing the siliceous "cuneiform group" with clays, V-7 to V-11. Woodward also omits the basal beds but draws the top at the base of the "cuneiform" zone. The lower sand and V-6 clay are persistent lithic reference planes in sections to the east and northeast. Probably the V-6 clay underlying 1–2 feet of commonly fossiliferous and calcarenitic beds are separated by disconformity from the barren argillaceous calcitite below, so belong "naturally" with the succeeding "Martinsburg", but the metabentonite is a more convenient and apparent boundary.

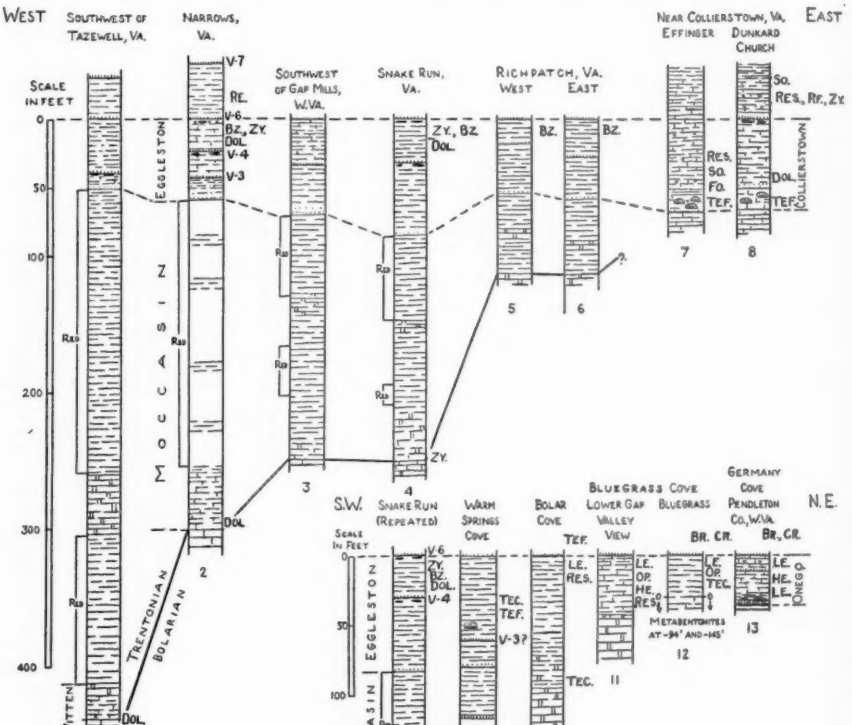
These units change as they are traced eastward to eastern Richpatch by way of Snake Run Cove east of Sweet Chalybeate, Virginia (Fig. 5): (1) the red color virtually disappears, (2) the thickness of the whole and of the parts decreases, (3) the McGraw limestone disappears beyond Snake Run, and the Moccasin lies on the McGlone in Richpatch, and (4) the lower Eggleston beds eastward contain occasional specimens of the massive colonies of the coral *Tetradium minus* Safford.

The next sections along this trend are in the Shenandoah Valley, near Effinger and Dunkard Church; the type section of the Collierstown formation (Cooper and Cooper, 1946) is at Effinger. No strata resemble the Moccasin, but the Collierstown is like the Eggleston in some respects. The lowest zone at Effinger is 14 feet of argillutite having irregular lensing limy beds and abundant large masses of *Tetradium minus* like those in the lower Eggleston to the west. Beneath are platy argillaceous calcilutite beds of the Edinburg formation; the lithology changes abruptly but the beds seem otherwise conformable. Above the *Tetradium* zone calcarenites and argillites contain such fossils as *Doleroides*, *Zygospira*, and *Foerstephyllum* ("*Columnaria*"). At Dunkard Church, a heavy calcarenite bed at 65 feet is partly silicified below a probable volcanic clay; as succeeding beds for 80 feet or more have *Sowerbyella*, *Resserella* ("*Dalmanella*"), *Rafinesquina*, and *Zygospira*, as well as gastropod coquinas, the metabentonite resembles V-6, but "cuneiform" beds were not recognized higher. The original description of the Collierstown formation (Cooper and Cooper, 1946, p. 104) gives thicknesses of 58 and 75 feet at Collierstown and Dunkard Church; the *Tetradium*-bearing zone was not mentioned but is here included in the unit. The Collierstown seems to correspond to the Eggleston.

Eastward, at the Barger Quarry within a mile southeast of Lexington about 60 feet of heavy-ledged calcarenite contains abundant rolled specimens of *Foerstephyllum*, *Lichenaria*, and *Solenopora* above well-bedded Edinburg argillaceous calcilutite much like that at Collierstown, and beneath argillaceous limestone with coquinas of the gastropod *Sinuites* like the beds overlying the type Collierstown. The coarse calcarenites seem a phase of the Collierstown and Eggleston. Cooper and Cooper (1946, p. 90) thought them older.

Sections southward from Narrows to Catawba Valley: Southward from The Narrows the sections in the Trentonian are in folds and thrust slices. The pre-Trentonian limestones in the belts near The Narrows (Cooper, 1944b) are succeeded by the Moccasin and Eggleston formations. They persist in eastern Sinking Creek Cove, but in place of a succeeding section of Moccasin, red calcareous argillutites and white-weathering calcilutites, and argillaceous Eggleston formation, the top of the Bolarian limestones by the Fish Hatchery is a disconformity with a few inches relief, under a few inches of pebbly quartz sandstone and a rather monotonous succession of drab, buff and brown-weathering argillaceous quartz siltstones and argillites. North of the creek, about 100 feet of these shales lies beneath metabentonites that have been correlated with V-3 in the basal Eggleston (Rosenkrans, 1936).

The next exposures southward are in Miller Cove in northwestern Roanoke County west of McAfee Gap (Woodward, 1932); the sequence has not been described in recent literature. Canadian dolomite rocks east of road 701 at the junction of road 704 are succeeded by about 100 feet of well-bedded dolomites and calcilutites that resemble the Lurich, then by about 100 feet of very heavy-ledged biostromal calcarenite with abundant massive bryozoans and sponges, resembling the Effna formation (Cooper, 1944b)



CONVENTIONAL SYMBOLS

FIGURE 5.—SECTIONS OF TRENTONIAN IN WESTERN ANTICLINES

1. Tazewell, Virginia, section along highway near Scales, Tazewell County, Virginia, principally from Cooper and Prouty (1943), with revision of lower beds.
2. Narrows, Virginia, beginning along Virginian Railway east of the New River north of Narrows, Giles County, extending to highway above.
3. Southwest of Gap Mills, Monroe County, West Virginia, on Hanging Rock Road south of road junction.
4. Snake Run, Alleghany County, Virginia, from slope south of road 600 about half a mile east of Iron Spring junction.
5. West Richpatch Cove, Alleghany County, Virginia, along road 616 east of Cliffdale along Blue Spring Run.
6. East Richpatch Cove, Alleghany County, Virginia, along road 620 about one-half mile west of Clifton Forge-Eagle Rock junction.
7. Effinger, Rockbridge County, Virginia, on slope north of highway at village store.
8. Dunkard Church, southwestern Rockbridge County, Virginia, from mountain slope south of church.
9. Warm Springs Cove, Bath County, Virginia, from bridle path bridge over Highway 220 at Homestead, Hot Springs.
10. Bolar Cove, Highland County, Virginia, from half a mile north of Jack Mountain road northeast of Bolar.
11. Lower Gap, near Valley View, Bluegrass Cove, Highland County, Virginia, from slope north of deep ravine half a mile east of gap.
12. Bluegrass, Highland County, Virginia, from slope a quarter of a mile north of the village.
13. Germany Cove, Pendleton County, West Virginia, from exposures along road .5 mile south of Harpers Gap junction and hill slope half a mile north; Benbolt and older beds from ravine between Seneca Caverns and Key.

Bz—bryozoans; Dol—*Doleroides* including some Pionodema; Fo—*Foerstephyllum*; He—*Hesperorthis*; Le—*Leptaena*; Op—*Opikina*; Re—*Resserella* ("*Dalmanella*"); Rf—*Rafinesquina*; So—*Sowerbyella*; Tec—*Tetradium clarki* Okulitch; Tef—*Tetradium fibratum* Safford and *T. minus* Safford; V—Metabentonites of Rosenkrans classifications; Zy—*Zygospira*

and phases of the Lincolnshire. The thickness of the overlying Bolarian shaly calcareous argillutite and argillaceous calcilutite was computed as 1,400 feet. The upper laminated argillaceous calcilutite beds are abruptly succeeded near the junction of roads 620 and 701 by Trentonian limestone-pebble-bearing, quartz arenaceous rock passing up into sparsely fossiliferous more argillaceous and shaly strata containing several metabentonites. The Trentonian rocks disconformably overlie the Bolarian and resemble those of Sinking Creek but are more sandy; they rest on very different facies of the Bolarian.

The Catawba Valley lies to the southeast. The limestones (Cooper, 1944b, p. 73–86) terminate in the coarse Effna calcarenite. The Bolarian rocks are dominantly argillaceous, bearing graptolites such as *Nemagraptus* and *Climacograptus* as well as the trilobites that have been attributed to the "Whitesburg" and "Athens" formations of Virginia (Butts, 1942; Cooper, 1953). The succeeding beds are argillaceous quartz sandstones with metabentonites that have been correlated with those in the Eggleston (Rosenkrans, 1936) and succeeding "Martinsburg" of the Narrows section. Hundreds of feet of "Martinsburg" argillaceous lutites and siltites exposed on the mountain road, Virginia Highway 311, bear few fossils, but occasional zones carry *Sowerbyella*, *Resserella*, and *Prasopora*.

The southeastern end of the Catawba Mountain syncline is near Cloverdale, Botetourt County. The Cloverdale and Catawba Railroad to the large limestone quarries in the Effna to the northwest has many exposures in the Trentonian sediments succeeding the "Athens". In the railroad cuts northwest of Cloverdale are hundreds of feet of quartz sandstones and a few conglomerate beds, having several metabentonites and occasional *Sowerbyella*-bearing calcareous intercalations.

The Moccasin and Eggleston formations of The Narrows seem to overlap southward, so that the "Cuneiform" Zone that lies more than 300 feet from the base in the north approaches the disconformable base in the south. Beneath this disconformity, the Bolarian beds change greatly from the distinct lithic units of the northern sections to the undivided argillaceous facies of the southern, and thicken greatly as they change. The Trentonian rocks coarsen southeastward.

Nealmont and Salona Formations

Sections northeastward to Pendleton County: The Moccasin, Eggleston, and succeeding Trentonian beds change greatly in the few score miles from Snake Run, Western Alleghany County, to Pendleton County, eastern West Virginia (Figs. 5, 6). The reddish and buff Moccasin retains its typical argillaceous lithology above McGraw limestone and beneath a basal Eggleston quartz sandstone only to the southern Warm Springs Cove. Above the Eggleston basal sandstone, a zone with *Tetradium minus* Safford and *T.* sp. cf. *T. clarki* Okulitch persists in Warm Springs Cove, and the corals are occasionally found northward to northern Germany Cove. An example is preserved in the roadside in front of Warm Springs Inn.

The beds occupying the position of the Moccasin of the southwest change northward to predominantly buff argillaceous calcilutite above a thin basal somewhat fossiliferous *Pionodema*- and *Doleroides*-bearing zone, then to interbeds of fossiliferous calcarenite and rather barren calcilutite, and finally to well-bedded fossiliferous somewhat argillaceous calcisiltite and calcilutite with a few coquinas. Thickness is constant.

The change of the Nealmont from the dominantly argillaceous Moccasin facies in the southeast to the typical Nealmont limestone facies in the northeast is shown in the restored section (Fig. 6); the reddish facies is prevalent in sections northeastward to Snake Run Cove (Tables 1–3). In southern Warm Springs Cove (Tables 5, 6), the beds between the Eggleston and the McGraw are buff argillaceous calcilutite, rarely with reddish bands and bands of white-weathering pure calcilutite. A metabentonite a foot thick lies about 30 feet below the base of the Eggleston basal quartz sandstone. In Bolar Cove to the northeast (Tables 7, 8) similar lithologies contain fossiliferous calcarenite, particularly well-exposed, shown on the hills 2 miles north of Bolar. Here and elsewhere there are reddish bands in the upper argillaceous beds. The succeeding beds are classed as Onego, for the quartz sands disappear, and *Leptaena* faunules occur below an upper metabentonite.

FIGURE 6.—RESTORED SECTION OF LOWER TRENTONIAN ROCKS

Similar rocks are associated a few miles to the northwest in southern Bluegrass Cove. The lower beds show best along a lane and ravine east of the anticlinal axis a mile east of Mill Gap water gap, and in scattered exposures west of East Branch north of the gap. West of the anticline and along the road a mile south of road 604 and Virginia Highway 84, the Nealmont contains large masses of *Tetradium* and *Foerstephyllum* ("*Columnaria*") and smaller nodular *Solenopora*. The higher beds are well shown along the slope north of the ravine east of Lower Gap, southeast of the junctions of roads 603 and 604 (Table 9). In the northern part of Bluegrass Cove, in several sections north and northwest of Bluegrass ("Crabbottom") village, the higher Nealmont contains a pair of foot-thick metabentonites about 140 and 180 feet from the base of the section of about 250 feet (Table 10), suggesting the metabentonites N-1 and N-2 in the top of the Oak Hall member of the Nealmont in Central Pennsylvania (Kay, 1944, p. 101).

The section in Germany Cove in Pendleton County, West Virginia, is similar; the metabentonite exposed west of Key (Table 11), evidently the lower of the two of Bluegrass, corresponds to clay N-1 of Pennsylvania. Calcilutite and buff-weathering calcareous argillutite are present in the upper beds northwest of Bluegrass; the argillutite shows columnar desiccation fractures, particularly at the hilltop north of the junction of roads 643 and 644. There is a little calcilutite along the roadside northeast of the road junction south of Key in Germany Cove. The Nealmont is dominantly thin-bedded calcisiltite having occasional coquinal beds with *Sowerbyella*, *Resserella*, *Hesperorthis*, and *Doleroides*. These coquina beds are well exposed along the roadside southeast of Harpers Gap and are like beds directly north of the junction of 643 and 644 northwest of Bluegrass and in the bank of East Branch above Mill Gap in southwestern Bluegrass Cove.

The oldest exposures in the Basore Cove in Hardy County, southeast of Mathias (Woodward, 1951, p. 227), are of Nealmont limestone. Exposures extend through tens of feet without showing the basal or upper contact. A few scattered exposures of Salona limestone are in the fields east of the anticline on the mountain slope east of Sheldon Spring.

The next succeeding unit, the Eggleston in the south, retains the quartz sandy base in Warm Springs Cove, but to the northeastward at the level of metabentonite V-6 of Warm Springs Cove, the top of the Eggleston, a metabentonite overlies beds having *Leptaena* and a large rafinesquinid brachiopod, *Öpikina* (?) sp. The succeeding beds have abundant *Resserella* ("*Dalmanella*"), and *Sowerbyella*, as well as coquinas with *Sinuites*, suggesting that the metabentonite is the same as V-6 of the Eggleston. Inasmuch as *Cryptolithus* is known immediately below this metabentonite in the *Leptaena* beds, there is resemblance to the Oranda formation farther east, and to the basal Salona below metabentonite 1 in Pennsylvania.

The beds from this metabentonite down to the base of calcarenites associated with species of *Tetradium* are here defined as the Onego member of the Salona formation, from the hamlet of Onego in West Virginia, a few miles northwest of the type section in the hillside north of Blue Grass, Virginia (Table 10). The Onego is believed to correspond approximately to the lowermost Salona of Pennsylvania, though it probably extends a little lower, to the Oranda of the Shenandoah Valley and to all but the lowest part of the Eggleston in the region of the New River. It has been called "Oranda" in an earlier paper (Kay, 1948). As the beds underlying the Onego are stratigraphically, faunally, and lithically similar to the Nealmont limestone of Pennsylvania, they are called the Nealmont formation. The Nealmont grades directly into the Moccasin formation southeastward. Possibly the lowest Onego is as old as the youngest Nealmont in Pennsylvania.

In northern sections the succeeding beds are well-bedded argillaceous calcisiltites and argillites, well exposed near the northern end of Germany Cove, particularly along the roadside a mile southeast of Harpers Gap junction in the cove, and on the mountain slope above the farmhouse about a mile east of the junction. They contain the trilobites *Cryptolithus* and *Brongniartella* and thus are like all but the very base of Salona beds in Pennsylvania. Much more frequent are coquina beds having *Prasopora*, *Sinuites*, *Resserella*, *Sowerbyella*, and

FIGURE 6.—RESTORED SECTION OF LOWER TRENTONIAN ROCKS

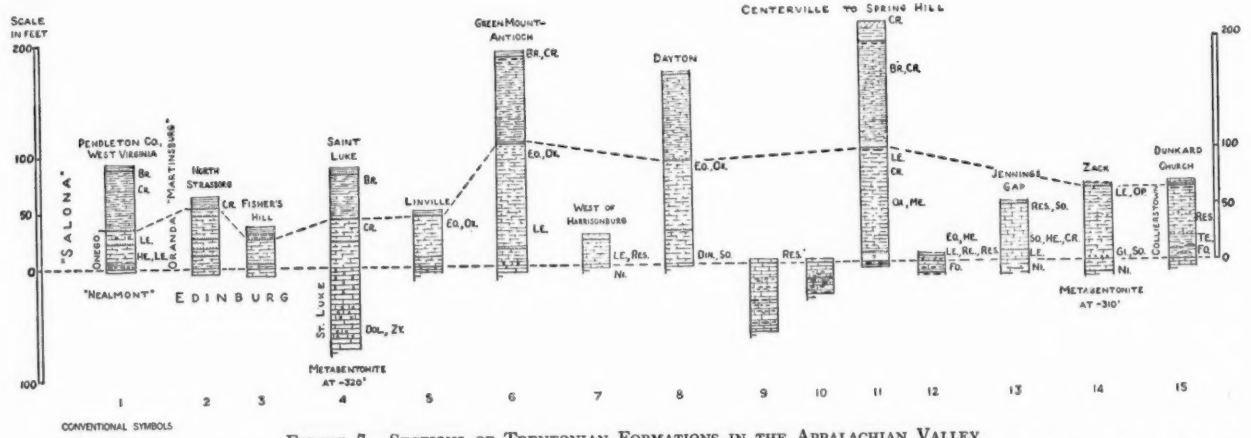


FIGURE 7.—SECTIONS OF TRENTONIAN FORMATIONS IN THE APPALACHIAN VALLEY

1. Pendleton County, West Virginia, for comparison, from exposures along road .5 mile south of Harpers Gap junction and hill slope half a mile north.
2. North Strasburg, Shenandoah County, Virginia, exposures along Highway 55 in northern part of town of Strasburg.
3. Fishers Hill, exposures along Highway 11 south of Tumbling Run, 1 mile southwest of Strasburg.
4. Saint Luke, Shenandoah County, Virginia, exposures north of stream east of the village.
5. Linnville, Rockingham County, Virginia, from slope east of axis of anticline half a mile north of station.
6. Green Mount-Antioch, section from exposures in fields between Green Mount Church and Antioch Church, 5 miles north of Harrisonburg, Rockingham County, Virginia.
7. West of Harrisonburg about half a mile in quarry south of road 33.
8. Dayton, Rockingham County, Virginia, from exposures east of old brickyard north of the town.
9. Centerville, Augusta County, Virginia, from exposures in field north of road directly west of village.
10. Ravine west of road about a mile southwest of Centerville.
11. Ravine northwest of road corner about 2 miles south of Centerville.
12. Hillside about 2.5 miles north of Spring Hill, Augusta County.
13. Jennings Gap, near Churchville, Augusta County, Virginia, from exposures along side road northeast of junction with Route 250.
14. Zack, Rockbridge County, Virginia, from exposures in slope south of ravine west of road about 1 mile north of county line in Augusta County.
15. Dunkard Church, southwestern Rockbridge County, from mountain slope south of the church.

Br—*Brongiartella*; Cr—*Cryptolithus*; Dol—*Doleroides*, including some *Pionodema*; Eo—*Eoplectodonta*; Fo—*Foerstephyllum*; Gi—*Girvanella*; He—*Hesperorthis*; Le—*Leptaena*; Me—*Mesotrypa*; Ni—*Nidulites*; Ox—*Oxoplecia*; Re—*Receptaculites*; Res—*Resserella*; So—*Sowerbyella*; Zy—*Zygospira*

Isotelus; *Amplexograptus* appears occasionally, as in beds east of the anticline a mile east of Lower Gap. The beds contrast with the shaly calcarenite beds of the "Martinsburg" of The Narrows, and the argillaceous shaly "Martinsburg" of Richpatch Cove.

TABLE 13.—SECTION BETWEEN GREEN MOUNT AND ANTIOCH CHURCHES, ROCKINGHAM COUNTY, VIRGINIA
(In feet)

	Thickness of unit	To base of formation
Trentonian Series		
Martinsburg or "Salona" formation:		
Argillaceous calcilutites, poorly exposed in fields north of road northwest of Antioch Church; lower beds in open field weathering to yield large faunule of free fossils; *see* Table 15.		
Dark argillaceous calcilutite, poorly laminated, having occasional specimens of *Brongniartella*; exposed in stream channels west of head of north-flowing stream	40	97
Crinoidal beds with abundant silicified *Cryptolithus* and *Calymene* succeeding argillaceous calcilutite	10	57
Metabentonite clay on strongly silicified ripple-marked surface	1	47
Argillaceous calcilutite, poorly exposed on slope west of broad open field with small stream	45	46
Metabentonite clay, hardly exposed but overlying rather continuously exposed ledge passing just west of stone farmhouse southwest of Green Mount Church and continuing southward in sinuous pattern	1	1
Oranda formation:		
Well-bedded, somewhat shaly argillaceous calcilutite, with abundant fossils; *Receptaculites* and glass sponges near top in well-exposed ledge; large faunule in underlying beds along lane southwest of house; *see* Table 15	60	75
Metabentonite-clay on silicified surface	.5	15
Buff-weathering argillaceous calcitite, somwhat calcarenitic and nodular near base; with frequent fossils; *see* Table 15; base has thin irregularly lensing clay	15	15
Disconformity (?)		
Bolarian Series (?)		
Edinburg formation:		
Gray, well-bedded somewhat argillitic calcisiltite, exposed along lane southwest of barn southwest of Green Mount Church		

Edinburg, Oranda, and Martinsburg Formations

Sections to the east in Augusta, Rockingham, and Shenandoah counties: Belts of outcrop of carbonate rocks along the west side of the Appalachian Valley and the east flank of the Elliott Knob synclinorium can be compared with those in the Western Anticlines (Fig. 7). From northern Shenandoah County to southern Rockingham, calcareous argillite, the Oranda formation (Cooper and Cooper, 1946), is very distinctive. The rocks below, to the top of the Lincolnshire limestone, are in the Edinburg formation, and those above have been classified as Martinsburg. Southwestward in southern Augusta and Rockbridge counties, the lithic and faunal equivalents of the Oranda are in the Collierstown limestone. The Oranda of western belts is similar to the Onego, and the "Martinsburg" is similar to the succeeding part of the Salona, but it is not clear whether the underlying Edinburg includes equivalents of all the Bolarian formations and the Nealmont or of only part. "The Edinburg is represented by beds . . . classified into the Ward Cove, Peery, Benbolt, Gratton, Wardell, Bowen, and Witten formations" (Cooper and Cooper, 1946, p. 86).

Oranda formation: The Oranda is calcareous argillite; its type section of about 50 feet is in the northern environs of Strasburg, northern Shanandoah County (Cooper and Cooper, 1946). Thickness ranges from about 25 feet to about 100 feet (Fig. 7). The pattern of the thickness distribution has not been ascertained in Virginia, though studied to the northeast, where it exceeds 150 feet (Craig, 1949). The Oranda contains metabentonitic clays. Several thin clays in the Strasburg section do not persist in nearby sections; but two clays lying on silicified surfaces persist through most sections

TABLE 14.—FAUNULES FROM THE ONEGO MEMBER OF THE SALONA FORMATION IN HIGHLAND COUNTY, VIRGINIA, AND PENDLETON COUNTY, WEST VIRGINIA

	Localities						
	1	2	3	4	5	6	7
Craniops	.	.	×	.	.	.	.
"Dalmanella" or *Resserella*	.	×	×	×	.	×	.
Doleroides (?)	×	.	×	×	.	.	.
Eoplectodonta	.	.	.	.	.	×	.
Hesperorthis	×	.	.	.	×	×	×
Leptaena	×	×	×	×	×	×	×
Öpikina	×	×	×	×	×	.	.
Oxoplecia	.	×	.	.	×	×	.
Reuschella	.	.	.	.	.	×	.
Sowerbyella	×	×	×	×	×	×	×
Strophomena	.	.	×	×	.	.	.
Zygospira	×	.	.	.	.	×	.
Calliops (?)	×	.	.	.	.	.	.
Calymene	.	×	.	.	.	.	.
Hemiarges	.	.	×	.	.	.	.
Illaenus	×	×	.	.	.	.	.
Isotelus	.	×	×	.	.	.	.
Eridotrypa (?)	.	×	×	×	.	.	.
Escharopora	.	.	.	×	.	.	.
Mesotrypa	.	×	×	×	.	.	.
Rhynidictya	.	×	×	×	.	.	.
Foerstephyllum	.	.	×	.	.	.	.
Streptelasma (?)	.	×	.	.	.	.	.
Aparchites	.	.	.	.	.	×	.
Eurychilina	×	.	.	.	.	×	.
Leperditia	.	.	.	.	.	×	.

(1) Ledge on hillslope north of Jack Mountain road near county line .6 mile east of Bolar, Bath Country; uppermost Onego; (2) Cut bank along stream .3 mile south of Trimble, Highland County; (3) Hillside north of ravine .5 mile southeast of Lower Gap, Highland County; upper 25 feet of Onego; (4) Ledge in old road bed east of highway .5 mile east of Mill Gap, Highland County; (5) Silicified ledge beneath metabentonite at top of Onego on hillslope .3 mile northeast of Bluegrass, Highland County; (6) Road cut, east side of road .8 mile south of Key, Pendleton County, from bed in upper 10 feet of Onego; (7) Hillside north of log shed east of Harman farmhouse, .8 mile east of Harpers Gap, Pendleton County; upper 10 feet of Onego

southwestward, one within the lowest few feet, the other at the top. The formation commonly is dark, somewhat calcareous argillutite in massive beds, though in some places the beds are quartz silty; it is rarely thin-bedded. The basal Oranda contrasts lithically with relatively purer calcitite of the Edinburg; disconformity on a small scale shows well in some contacts, as on the hill west of the road half a mile west of Highway 11 near Pike Church, southwest of Harrisonburg, and east of the road junction 2.4 miles north-northeast of Spring Hill and about 4 miles southwest of Centerville.

The Oranda is quite fossiliferous, commonly bearing species of *Leptaena*, *Resserella*, *Oxoplecia*, *Dinorthis*, *Hesperorthis*, *Praspora*, and *Solenopora*, and in the upper part *Eoplectodonta* and *Öpikina* (?) as well. *Cryptolithus* is found in the uppermost beds in some exposures (Table 15). However, these forms are not limited to the Oranda, and most of them recur 100 feet or more higher, seen best in the fields between Antioch Church and Green Mount Church (Table 13), 5 miles north of Harrisonburg. The southernmost locality to yield *Cryptolithus* is the roadside cut northeast of Jennings Gap; *Leptaena* is in thin limestone beds 4 feet above *Nidulites*-bearing argillaceous calcilutite and 5 feet beneath a clay parting, probably metabentonite; *Cryptolithus* is with *Sowerbyella*, *Hesperorthis*, and *Resserella* 8 feet higher.

It has not been determined whether the Oranda lies on synchronously laid beds, or on a regional unconformity bevelling the Edinburg formation. The underlying beds vary considerably. In the type area of the Oranda and Edinburg, they are barren, well-bedded argillaceous calcilutite. Near St. Luke, 4 miles west of Woodstock *Zygospira*, *Doleroides*, and *Solenopora* are frequent in calcarenite about 65 feet below the base of the Oranda; most of the succeeding rock is heavy-ledged pure calcilutite. This is the type section of the "St. Luke limestone member of the Edinburg" (Cooper and Cooper, 1946). Similar calcilutite is present near Green Mount and Antioch churches, north of Harrisonburg. East of Glade Valley, between Centerville and Spring Hill, several chert-nodule zones in the upper part of the Edinburg are associated with plane-surfaced

silicified beds beneath metabentonites (Fig. 8, sections 9–11). A conspicuous metabentonite is about 10 feet below the top on a silicified surface northeast of the road corner 2 miles from Spring Hill. Several beds are well displayed in a small ravine about 2 miles southwest of Centerville. Beds in the several sections have not been successfully correlated.

Nidulites-bearing beds are present at varying distances below the Oranda. A prominent metabentonite on a chertified surface lies 330 feet below the Oranda near St. Luke, 175 feet above the black chert nodule-bearing Lincolnshire limestone. In a section by the old brick plant east of the road north of Dayton, a foot-wide gap with adjoining chertified calcitite about 200 feet below the Oranda probably represents a metabentonite. Whether the gap represents clay like that near St. Luke is not established. Similar cherts are present through 50 feet of calcitites, north of the road west from Centerville.

The relations between the Oranda-bearing sections and those southwest of Lexington having the Collierstown formation must be interpreted through intervening sections exposed best near the southwestern county line of Augusta County west of Walker Creek southwest of McKinley and northeast of Zack store. Along the road about half a mile north of the county line the Edinburg has a thick metabentonite associated with phosphatic pellet beds about 150 feet from the base; on the hillside south of the farmhouse west of the road another metabentonite having a black chert-bearing underlying calcitite succeeding *Echinosphaerites*-bearing beds occurs 200–250 feet higher. The succeeding beds are excellently shown on the ridge southwest of the farmhouse (Fig. 7); 330 feet of argillaceous calcilutite and calcisiltite extend from the upper chert to the base of a 5-foot *Girvanella*-bearing calcarenite. *Receptaculites* and *Echinosphaerites* are common in the Edinburg about 250 feet above the metabentonite, and *Nidulites* about 55 feet higher, 25 feet from the top. The *Girvanella* bed, which also contains *Foerstephyllum*, lies with sharp contact, probably disconformably, on the underlying calcitites; the contact is well shown also on the hillslope a quarter of a mile to the north. The succeeding rather shaly argillaceous calcitites have thin beds with *Sowerbyella* and massive *Prasopora*-like bryozoans. *Sinuites*-bearing calcitites and beds of calcisiltite with small worm borings are frequent above 50 feet to about 100 feet, where there is a prominent clayey zone; *Leptaena* and *Öpikina* (?) are rare

TABLE 15.—FAUNULES FROM THE ORANDA AND MARTINSBURG FORMATIONS IN ROCKINGHAM COUNTY, VIRGINIA

	Localities					
	1a	1b	1c	1d	2	Onego
"Dalmanella" or *Resserella*	×	..	..	×	×	×
Eoplectodonta	..	a	..	c	×	×
Leptaena	×	×	..	×	×	×
Öpikina	..	..	..	×	×	×
Oxoplecia	..	c	..	×	×	×
Plectorthis plicatella	..	×	..	a	..	..
Rafinesquina	..	..	..	×	..	..
Reuschella	c	..	..	..	×	×
Sowerbyella	×	×	..	c	×	×
Strophomena "conradi"	..	..	..	..	×	..
Amphilichas	..	..	..	..	×	..
Brongniartella	..	..	c	×	..	..
Calliops (?)	..	..	..	×	..	×
Calymene	..	..	..	×	..	×
Cryptolithus	..	..	a	c	×	..
Encrinurus	..	..	c	..	..	..
Receptaculites	..	×	..	..	..	..
Eridotrypa	×	..	..	..	..	×
Mesotrypa	×	..	..	×	..	×

(1) Between Green Mount Church and Antioch Church, 5 miles north of Harrisonburg; la. Lower Oranda along lane west of house on private lane southward from Green Mount Church; (1b) Top beds of Onego just west of lane by farmhouse; (1c) Beds within 20 feet above metabentonite on west slope of hill about .3 mile south of farmhouse; in "Martinsburg" formation; (1d) Fossils weathered from calcargillites in open field north of road running west of Antioch Church, about .5 mile south of farmhouse; (2) Silicified top beds of Oranda crossing ravine below road about .8 mile south of Centerville; (Onego). Listed faunules from Onego member of the Salona formation of Western Anticlines in Table 8.

in the upper part of this shaly sequence; and a loose block of *Tetradium* sp. cf. *T. fibratum* (Safford) was found on the surface. The lithology and thickness of these beds resemble the Collierstown, though Cooper and Cooper (1946, p. 102) assign only 40 feet to the Collierstown in this section. *Leptaena* and *Öpikina* (?) are as in the Oranda, though also in younger Martinsburg at Green Mount Church and Centerville. Thus, the Oranda is probably within the upper part of the Collierstown, and the metabentonite at the top of the Oranda is probably the same as that at the top of the Collierstown at Dunkard Church, in southern Rockbridge County. The lower beds resemble the St. Luke member of the Edinburg in western Shenandoah County.

In the Western Anticlines, the Oranda closely resembles the higher part of the Onego, though the Onego is lithically more like the Collierstown. The lower part of the Onego seems equivalent to the lower beds of the Eggleston and Collierstown; the base of the Onego resembles that of the St. Luke limestone in the upper Edinburg. The *Leptaena* metabentonite at the top of the Onego with the faunal associations so resembles that at the top of the Oranda that they must be the same; the lower Oranda metabentonite can then be compared to that lower in the Onego.

The St. Luke seems an easterly continuent of the lower Onego, but equivalent beds may be missing in sections farther eastward and southward until reintroduced as the lower Collierstown in southwestern Augusta County. The bases of the Oranda, Collierstown, and St. Luke under this hypothesis would lie on a regional unconformity at a lower stratigraphic level than where below the Nealmont in the Western Anticlines.

Martinsburg formation: The beds succeeding the Oranda form the typical Martinsburg formation, for the name was first applied (Geiger and Keith, 1891) in the West Virginia panhandle just north of the Shenandoah Valley belt of Virginia. At Strasburg, as at Martinsburg and northward into Pennsylvania (Craig, 1949), the rocks are preponderantly dark, laminated, calcareous argillite-shale. At Fishers Hill, 1.5 miles southwest of Strasburg, a pair of 6-inch and 10-inch metabentonites with an intervening foot of *Cryptolithus*-bearing somewhat silicified argillite directly succeed the Oranda (Fig. 7); thin metabentonites are at several horizons in the succeeding 100 feet (21, 34 and 71 feet in northern Strasburg). At St. Luke, the Martinsburg is similarly calcareous shale, having *Cryptolithus* in the 16 feet between the 10-inch metabentonite near the base and the foot-thick one above; 41 feet higher, 60 feet from the base, a third metabentonite, 10 inches thick, has rare specimens of *Brongniartella* below it; this trilobite is frequent between metabentonites Nos. 4 and 6 in the Salona formation of Pennsylvania (Kay, 1943).

Excellent sections of the post-Oranda beds are displayed on the hills between Green Mount and Antioch churches 4 miles north of Harrisonburg, and in the ravine northwest of the road corner 2 miles south-southwest of Centerville (Fig. 7). The first has a chert-based thick metabentonite about 60 feet from the base; *Cryptolithus* is abundant in the underlying beds, and *Brongniartella* frequent about 20 feet higher, at about 80 feet in the formation. A rich faunule of free-weathered specimens of *Dinorthis*, *Leptaena*, *Resserella*, *Öpikina* (?), *Eoplectodonta*, and *Cryptolithus* is in calcareous argillite between 130 and 150 feet from the base of the section of the formation (Tables 13, 15), and scattered exposures continue for more than another 100 feet, with *Cryptolithus* present to the top. The Centerville section is even better exposed; a prominent chert-based metabentonite about 95 feet from the base of the formation overlies *Cryptolithus* and *Brongniartella*-bearing argillaceous calcilutites; similar beds in near-by localities have *Leptaena* and *Dinorthis*. A silty, cobbly-weathering 10-foot zone is 12 feet higher, and *Cryptolithus* and *Dinorthis* are frequent to the top of good exposure about 150 feet above the base of the formation. These sections of the Martinsburg formation are more like the Salona formation of the Western Anticlines and central Pennsylvania than the typical Martinsburg shale northward in the Shenandoah Valley structural belt.

Classification and Correlation

Stratigraphers have differed in their classifications of the strata in the Western Anticlines;

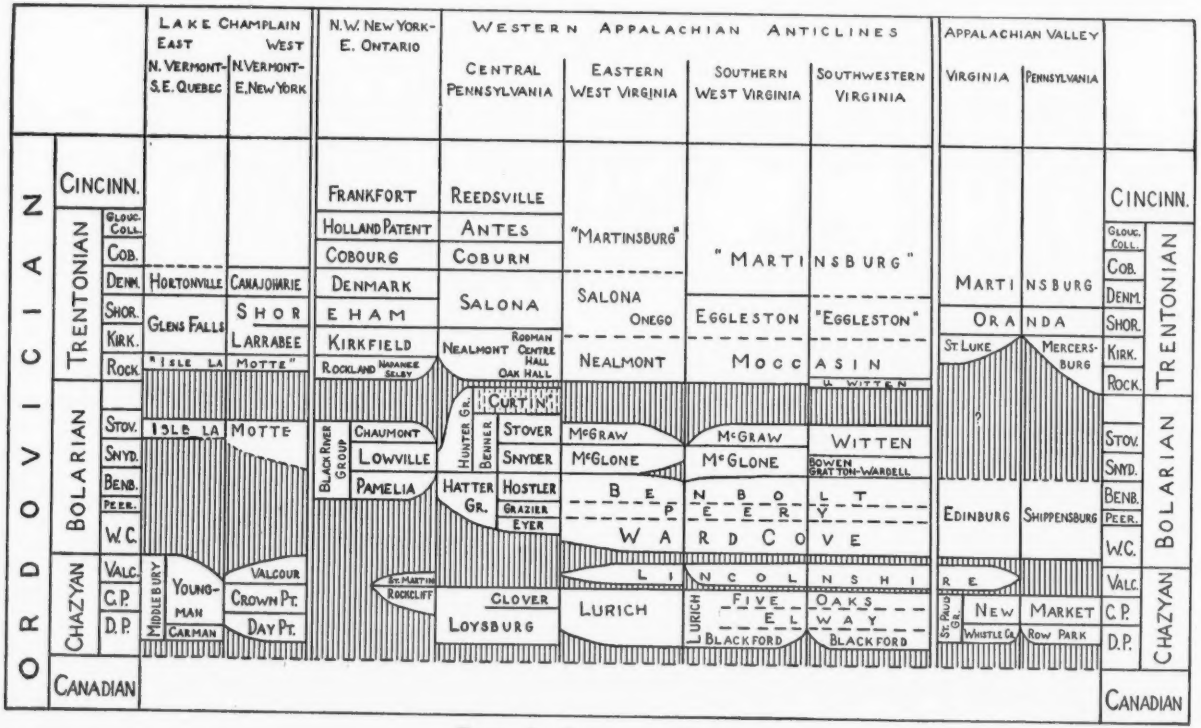


FIGURE 8.—CORRELATION TABLE

* Recent studies by Rones (Personal communication) in Pennsylvania show that the Curtin limestone is synchronous with part of the Nealmont limestone.

their conclusions reflect the influence of varying experiences with lithologies and faunas, and of differing principles and methods. The classification of the writer (Fig. 8) lies within extremes.

The classification of the sediments requires correlation in time with standard sections in New York and Ontario. The standard of the Chazyan is east of the Adirondack Mountains, that of the Trentonian on the west[3]; thus, classification involves correlations within the Adirondack-St. Lawrence region as well as to it. The Bolarian Series, though named from Virginia, is defined as including rocks between the Chazyan and the Trentonian.

The possibilities of establishing synchroneity of horizons in sections far apart by either lithologic or paleontologic means are very limited. Knowledge of the ranges of fossils is gained from stratigraphic evidence, hence fossil-based correlations are dependent on experience. Evolutionary changes in organisms are never so universal and instantaneous as to permit establishment of precise synchrony. Within limited regions, lithic evidence can permit recognition of chronologically identical horizons, though judgments can differ on whether specific lithic likenesses are of great time significance. Some units and sequences of unlike units are very constant in lithology and thickness along trends, suggesting stability of environments through spans of time along the trend. Other units change so rapidly vertically and horizontally as to demonstrate their more varied and temporal environments. The limited number of volcanic ash beds in the Western Anticlines should establish synchrony at several horizons, but one can err from section to section by vertical shifts of one or more ash beds, or be misled by lateral additions or subtractions.

In the Western Anticlines the youngest formation classified as Chazyan is the Lincolnshire limestone. The base of the Nealmont formation in the northern sections of the Western Anticlines is judged to be basal Trentonian. The contact of the McGraw limestone on the McGlone limestone within the Bolarian Series is correlated in time with that between the Chaumont and Lowville limestones in the Black River group of northwestern New York. The Ward Cove formation is Bolarian and is considered older than the base of the Black River Group in New York, though younger than the Valcour limestone at the top of the type Chazyan. The Onego formation, above the Nealmont, is about equivalent to the Shoreham limestone of the Trentonian in New York.

Woodward (1951, p. 149) placed the Peery and older formations in the "Chazy Group", the Benbolt, McGlone, and McGraw in the "Black River Group" (as interpreted from his sections in Highland and Pendleton counties on p. 318–322), and succeeding beds in the "Trenton Group". Cooper and Cooper (1946, p. 70, 77) in the Shenandoah Valley classed the New Market as Chazy, the succeeding Whistle Creek "if at all Chazy, only upper Valcour", and the succeeding Lincolnshire as probably younger than Chazy and possibly equivalent to part of the Black River. B. N. Cooper (1950, p. 32) wrote that the "Lincolnshire does contain some Chazy fossils". Neuman (1951) reversed the order of the lowest beds, considering the Whistle Creek and correlated Row Park

[3] Differing statements about the relations of late Black River and early Trenton limestones in northwestern New York and southern Ontario reflect not only varied interpretations but inconsistent nomenclature. The Coboconk formation in central Ontario, originally the "Leray" or "Black River", contains 35 feet of limestone, the lower 20 feet exposed at Coboconk (Johnston, 1911, p. 140) and the higher beds underlying Kirkfield "Dalmanella beds" at Dalrymple (Johnston, 1912, p. 255–257). Kay called this Coboconk Rocklandian (1937, p. 256–257). Okulitch, describing only the lower Coboconk, believed the lowest 7 feet to be Black River, the succeeding 15 feet doubtfully Rockland, on *faunal evidence* (1939, p. 337–338). Kay *traced* the underlying Moore Hill limestone (Okulitch, 1939) with *Tetradium cellulosum* (Hall) into the type Chaumont of New York (Kay, 1942a, p. 596); a western Chaumont section in typical lithology is 26 feet at Crookston, north of Belleville. Sinclair (1954) from *faunal analysis* judged the Kirkfield to be Rocklandian, though *Triplesia cuspidata* (Hall), normally found in upper Rockland, is in the "upper Coboconk" (Kay, 1942a, p. 602, loc. 6). Kay's statement that he revised the type Rockland (1937, p. 251) was later recognized to be an error (Kay, 1942a, p. 599). The Coboconk limestone and the upper "Black River" in Ontario are lower Trentonian Rocklandian. The Kirkfield formation has been mapped in New York as post-Rockland (Kay, 1953), and Kirkfieldian has been used as a stage succeeding the Rocklandian in the Trentonian series.

The Isle la Motte limestone was classed as Rocklandian (Kay, 1937, p. 260–261) but is now thought to be upper Bolarian, Chaumont equivalent; but the 16 feet of beds called Isle la Motte at Crown Point (p. 254) are Rocklandian.

to be Middle and doubtfully Upper Chazy, the New Market to be lowest Black River (Pamelia), and thus the Lincolnshire to be within the Black River, though lacking an equivalent in the type section. Thus the disposition of Lincolnshire has ranged from well down in the Chazyan to well above the base of the Black River Group.

The Black River Group of northwestern New York has three formations, the Pamelia, Lowville, and Chaumont (Young, 1943) (Fig. 3). The Chaumont has heavy ledges of very dark, fine-textured calcitite with generally undulating bedding planes and distinctive ramifying rod-shaped bodies of more magnesian and silty calcitite that weather to form holes. These rod-shaped structures are called "fucoidal", placed in the genus *Camarocladia* (Pl. 2, fig. 4). The contrast of the Chaumont limestone with the underlying Lowville limestone is abrupt, for the Lowville is dominantly light-gray, almost white-weathering calcilutite with frequent colonies of the coral *Tetradium cellulosum* (Hall). The difference between the two formations persists westward into Ontario for a few score miles, then diminishes as the Chaumont becomes less fucoidal and has interbeds of lighter calcilutite (Kay, 1942a); the section at Napanee and Crookston retain the typical fucoidal structures.

The Snyder and Stover limestones (Kay, 1943) in Pennsylvania, and the McGlone and McGraw limestones in the Virginias have similar contrasts to those of the Lowville and Chaumont. Not only is the upper of each pair made of *Camarocladia*-bearing calcitite, but the lower is *T. cellulosum*-bearing, and largely of calcilutite. This presence of *T. cellulosum* is more a confirmation of similarity of environment of deposition than a significant indication of synchrony, for the species has extended range. A very widespread physical change in a tectonically rather stable region could bring about such a contrast in persisting peculiar lithologies.

In New York and Ontario, carbonaceous, somewhat siliceous and argillaceous calcitite, the Selby member of the Rockland formation, lies disconformably on the Chaumont and forms the base of the Trentonian; it is best seen beneath the bridge in Lowville, New York. The most common and distinctive brachiopod, *Doleroides*, persists in similar rocks in the base of the Nealmont lying on the eroded Stover in southern Pennsylvania and on the McGraw in the Virginias.

As much as 150 feet of high-grade calcilutite, the Curtin limestone, intervenes in the northwestern outcrops in central Pennsylvania between the Stover and well-bedded Centre Hall member of the Nealmont limestone with Trentonian fossils (Kay, 1948; 1943). The writer interpreted this unit as lying beneath the regional unconformity that places the Nealmont on beds as old as Snyder limestone to the southeast. Norman Rones of Pennsylvania State University has demonstrated to the writer's satisfaction that the surface at the top of the Curtin is intraformational, and that the Curtin chemical limestone is time equivalent to the lower Oak Hall limestone of the Nealmont. The pre-Nealmont regional unconformity is recognized to the southeast. Thus the Curtin is a calcilutite facies of the lower Nealmont just as there is calcilutite in the Moccasin facies of the Nealmont in the Virginias. The Hunter Group (Kay, 1948) is not significant, and Benner Group should be applied to the upper Bolarian.

The base of the Trentonian is drawn at a persisting disconformity underlying the Nealmont; *Doleroides* and *Pionodema* persist above this surface into southern Virginia. The surface bevels varying thickness of calcitites succeeding the rather pure calcilutites of the Lowville-Snyder-McGlone and the darker *Camarocladia*-bearing Chaumont-Stover-McGraw units (Fig. 3). The interval ranges from absence in the Mohawk Valley of New York, southeastern sections in central Pennsylvania and in the Virginias, to about 150 feet in central Pennsylvania near Bellefonte. The most extensive sequence in central Pennsylvania seemed to have one unit, the Curtin, younger than Chaumont and older than the Trentonian, but the recent studies show this interpretation to have been wrong. The top of the underlying Stover limestone may be somewhat younger than that of the thinner Chaumont. The base of the Chaumont—the top of the Lowville—seems to be a time-stratigraphic plane that can be traced far to the southward.

Correlation and classification of older beds are more uncertain. If the Chaumont-Stover-McGraw correlation is correct, the beds below the Snyder and the McGlone occupy a stratigraphic position similar to that of the Pamelia. Yet there is little lithic or faunal similarity between the Ward Cove-Peery-Benbolt succession and the Pamelia. About the only evidence directly suggestive of equivalence is that the northern sections of the Hatter in Pennsylvania, thought equivalent to the Benbolt, have magnesian limestone and fine-grained dolomites, resembling those in the Pamelia in New York. The sparsely fossiliferous Pamelia is closest faunally to the New Market limestone of the Shenandoah Valley (Neuman, 1951, p. 304) and to the correlated Loysburg limestones of Pennsylvania and the Lurich of the Western Anticlines of the Virginias. *Tetradium syringoporoides* is common to these units; *Fletcheria sinclairi* (Okulitch) was additionally cited (Neuman, 1951, p. 305) but is from the Lowville in its type appearance in Ontario (Kay, 1942a, p. 593). *T. syringoporoides* is restricted to the Pamelia in New York only if one defines the Lowville as excluding beds containing the fossil (Neuman, 1951, p. 305); it appears widely below *T. cellulosum* and hence seems to represent an earlier stage; it is in the Five Oaks and the Peery in southwestern Virginia (Cooper and Prouty, 1943, p. 866). Direct evidence does not limit its earliest appearance to the base of the Pamelia. If the correlation of the Lincolnshire with the Upper Chazyan Valcour limestone be correct, the underlying New Market and Loysburg must be Chazyan. And if they are post-Chazyan, the Lincolnshire must be younger! The writer correlates the Lincolnshire formation with the upper Chazyan Valcour formation of Vermont. The St. Martin limestone that underlies Pamelia in the Ottawa Valley has been classified as Valcouran (Wilson, 1946).

Northward toward and into Pennsylvania the stratigraphy suggests that the Lincolnshire is succeeded in the Western Anticlines by disconformity, which surface is onlapped by successive lower Bolarian units that are older than much of the Black River Group; it is thought that beds equivalent to the Benbolt pass into the Pamelia northward. This places the Lincolnshire below the base of the Black River Group of the New York outcrop but does not make it equivalent to the Chazy.

The correlation with the Valcour is supported by the presence of *Billingsaria* in the upper Lincolnshire reefs just as in the Valcour reefs, whereas species of *Tetradium* and *Foerstephyllum* appear in the next higher coralline beds seen, in the Benbolt and in the typical Black River, particularly the Chaumont. There are many seeming contradictions. The Lincolnshire has *Sowerbyella* (Cooper and Cooper, 1946, p. 77), known in the north only in Trentonian and younger beds, and *Strophomena*, there found in Black River and younger. *Sowerbyites* is unknown in New York. On the other hand, there are genera in the Lincolnshire that are not known in the type Chazy west of Lake Champlain. "The trilobites which have been identified from the (lower middle Ordovician) formations include a number of typical Chazy species whose presence would seem to conflict with some of the correlations worked out on the basis of brachiopod genera" (B. N. Cooper, 1953, p. 4). The writer's experience with the Chazyan along Lake Champlain leads him to conclude that some of the genera lacking in the type Chazy are represented in more argillaceous facies in western Vermont and southeastern Quebec (Kay, 1945), on which publication is being prepared.

The writer believes that the Lincolnshire disappears northward beyond the northern exposures along the Western Anticlines in Pendleton County, West Virginia, and is older than the Pamelia, which he correlates with the Benbolt formation, separated from the Lincolnshire by the northwardly overlapped basal Bolarian Ward Cove and Peery formations. The ranges of *Billingsarea* and *Foerstephyllum* on the one hand suggest that it is Chazyan; if correctly interpreted, *Tetradium syringoporoides* is pre-Lowvillian but ranges down into the low Chazyan. Its absence in the New York Chazy seems not surprising, for it is associated with lithology reflecting environment not represented along Lake Champlain.

The correlation of the Onego with the Shoreham (Kay, 1937; 1953) is based on several criteria. Some of the fossils are contradictory. *Reuschella* is known in both units and is restricted to them and Appalachian Valley

Oranda formation. *Cryptolithus* is not normally present in the Onego and Oranda in the Virginias but is frequent in beds classed as Oranda in Pennsylvania. Several of the associated forms are in the basal Salona in Pennsylvania, overlain by *Trocholites*; cephalopod-bearing beds much like those in basal Denmark limestone above the Shoreham in New York—but *Trocholites* ranges from the lowest Trenton in New York. Some genera, such as *Hesperorthis*, are known only in pre-Shoreham Trentonian in New York and Ontario. The succeeding "Salona limestone" of the Western Anticlines is of course correlated with the typlcal Salona of Pennsylvania and in time with the Denmark limestone in the middle Trenton of northwestern New York. Several metabentonites are present throughout the belt and can be correlated, but the correlations have been made largely on the limited reported range of *Brongniartella trentonensis* (Collie) between clays Nos. 4 and 6 in central Pennsylvania, a criterion that cannot be confidently applied to distant localities.

The main bases for correlation seem to be lithic and to a lesser degree faunal, interrupted continuity—tracing or "walking out"—along a belt from Virginia to northwestern New York in which some units retain quite constant lithic characters, whereas others change. One cannot prove such correlations, but they seem the most reasonable. To review the propriety of the correlations, the critic should examine sections at one end of the trend, as at The Narrows, go along the Allegheny Front to Germany Valley, jump the intervening structurally depressed area adjoining the Wells Mountain anticline, trace the units northeastward in central Pennsylvania, and make the even greater jump to the West Canada Creek and Black River valleys. He may be impressed as is the writer by the great similarities among lithologies in some parts of sequences, and differences in others.

Some of the correlations must be made by means of fossils, particularly those of the older beds that seem to thin or disappear northward, hence are isolated from standard sections in New York. These fossil-based correlations again involve judgments and experiences. The ranges of genera are continually being extended, particularly as varied facies of standard units are studied. The conclusions are not unequivocal.

The correlations can be compared with those proposed by Woodward (1951) for the same area. Woodward and the writer each spent parts of several field seasons in study of the Ordovician rocks in the Western Anticlines, but did not compare results until subsequently. The classification of the units, and their correlations with southwestern Virginia standards, shows rather close agreement. Woodward applied numbers to the units that compare as follows with the names in the present paper: Lurich: 1–4; Lincolnshire: 5; Ward Cove: 6; Peery: 7; Benbolt: 8A, 8B; McGlone and McGraw: 8C, 8D; and Nealmont: 9, 10. These identifications are based on direct comparison with Woodward's sections in Highland County, Virginia, and Pendleton County, West Virginia (1951, p. 316–322) rather than statements in the text. Thus, Woodward states that bed 9 is "the Witten formation of Cooper and Prouty", but it falls within beds classed by the writer as Nealmont, directly above a regional disconformity that both Woodward and the writer recognize; the writer judges that part of the Witten of southwestern Virginia is older, in the McGraw and McGlone.

Woodward classed the Lincolnshire as Chazyan, the Benbolt, McGlone, and McGraw as Black River, and the Nealmont as Trentonian. The Ward Cove and Peery he called Chazyan; the writer, though considering them pre-Pamelia, believes them post-Chazyan, hence uses Bolarian for the series. Differences are great with respect to correlations with Pennsylvania, for Woodward considers the Lincolnshire to be represented in Lower Hatter (Eyer-Grazier) and the Virginia units to correlate to higher levels than judged by the writer. Thus, he correlated the Benbolt and McGlone with the Curtin, instead of with the Snyder-Stover (Woodward, 1951, p. 149); but the Curtin is now recognized as a facies of the Trentonian Nealmont.

Paleogeography and Tectonics

The lithic sequences have been described, and their correlations and classifications interpreted. The following history of the region is based on these facts and inferences. The dominant tec-

tonic trend generally paralleled the Allegheny Front, for similarities are greater among sections in the parallel Appalachian Valley a few tens of miles to the southeast. Some units show local lithic variation. The Lincolnshire reefs pass into detrital calcarenites and calcisiltites; a significant pattern has been recognized. The Ward Cove and Benbolt limestones also change along the outcrop, without evident geographic pattern; the Ward Cove thins appreciably northeastward. The most striking change in facies is in the lower Trentonian; the Moccasin red and buff argillaceous calcilutites and calcisiltites pass into bedded fossiliferous Nealmont limestones to the northeast. Other units are more constant. The upper Lurich Five Oaks calcilutite and the upper Bolarian McGraw limestone represent deposition in quite stable environments in contrast to the varying conditions shown by the lithofacies of the intervening and succeeding sediments. Several volcanic ash beds altered to metabentonite permit precise correlations within the Trentonian. Regional unconformities represented by local disconformities are extensive at several levels.

The Chazyan Epoch is represented in two stages, the Lurichian and the Lincolnshirian; their deposits are bounded by erosion surfaces. The Bolarian Epoch also has two stages, the earlier (Hatterian) marked by relative southeasterly regional tilting, and the latter (Bennerian) by gradual northwesterly tilting. The deposits of the Trentonian Epoch are introduced by the Nealmontian Stage, having quite varied lithologies, the more coarsely terrigenous produced from rejuvenated highlands to the southeast and south; the sediments lie on a regional disconformity increasing in stratigraphic gap eastward and southward. The Ordovician limestones terminate with sediments of Shorehamian and Denmarkian age that become more argillaceous southeastward.

The Lurich formation lies with disconformity on the Canadian dolomites, the surface having local relief of scores of feet; the lowest beds commonly bear chert fragments, detritus from erosion of cherty carbonate rocks like those below. Thicknesses in the Loysburg do not show a marked trend that indicates a pattern of systematic deformation. The Lurich generally progresses upward from dolomites, some quartz-sandy and quartz-silty, into calcilutites, having decreasing portions of black chert; darker, somewhat more fossiliferous calcitites are in the correlated Row Park and Whistle Creek formations of the Shenandoah Valley. Relations suggest that more open marine waters were south and east of the Western Anticlines; shores were an unknown distance to the northwest and trended northeastward between equivalent rocks in Pennsylvania and the New York outcrop where they are missing. The last Lurich deposits seem everywhere to be calcilutite with such minor erosion that this upper unit seems unfailingly retained.

The Lincolnshire is calcitite throughout its extent, which is south of an ill-defined line trending westward, perhaps southwestward, from about the Virginia-West Virginia line at the Shenandoah Valley. The formation seems to be missing in Pennsylvania and locally in southern West Virginia, thickening to about 50 feet within a mile in southern Monroe County. Thickening must be by addition of older beds, the formation onlapping, for reefy beds are seen at scattered localities only at the top; they may represent local shoaling, as in Vermont and New York (Oxley, 1951); they are in the top of sections of 40 feet or less in Monroe and southern Highland counties, but in sections of 150 feet or so in northern Alleghany County. The biohermal beds pass into calcarenite facies within short distances. There seems to be disconformity at the top of the Lincolnshire, for the succeeding Ward Cove at the base of the Bolarian Series overlaps, but erosion was slight. The formation thickens into an area of greater subsidence toward the south and east.

The Bolarian Epoch introduces distinct tectonic change. The rocks thicken southeastward across a flexure that trends somewhat more westerly than the trend of the Western Anticlines. The Ward Cove is thin in the Germany-Bluegrass anticline, but thicker in Richpatch. The increase seems due both to divergence and onlap. The thin quartz-silty facies of the northwest seems continuous into the lowest Hatter beds in southern Pennsylvania, the Eyer quartz-silty calcitites in the Bedford area, which are overlapped by younger units into central Pennsylvania.

The Peery formation is important as a probably time-stratigraphic unit giving a datum within the Bolarian sequence. The seeming continuity of black chert-nodule-bearing quartz-silty argillaceous calcitite with *Polylopia* has led to this assumption. The succeeding Benbolt is quite variable in lithology and composition, perhaps mostly quartz-silty argillaceous calcisiltite, but frequently more argillitic or more calcarenitic, and occasionally quite biohermal with abundant heads of bryozoans and coral, as well as frequent sponges. The only rather constant lithic unit is the uppermost cross-laminated fine quartz and calcite arenite; it is not precisely time stratigraphic. It was thought there might be a relation between, say, thinness of the Benbolt and abundance of sponges, bryozoans, and corals, but none was recognized. The formation is sparsely cherty. The Ward Cove-Peery-Benbolt succession of southeastward-thickening impure limestones has been considered to pass into the thicker "Athens" shaly calcareous argillite of Miller Cove and Catawba Valley. The gradation of the correlated Edinburg limestone of the Shenandoah Valley into the "Athens" or Liberty Hall facies has been described (Cooper and Cooper, 1946, p. 79). The main tectonic character of the region of earlier Bolarian time is the southeastward increase in thickness into a miogeosyncline, along a flexure passing somewhat parallel to, and east of, the Western Anticlines. Introduction of terrigenous material to the southeast has been attributed to the Blountian orogeny (Kay, 1942b).

The younger Bolarian formations, the McGlone and McGraw limestones, present quite a contrasting pattern of deformation, for they thicken northwestward, just as has been ascribed to their correlatives, the Snyder and Stover, in Pennsylvania. As the base of the McGraw seems to be a distinctive lithic boundary that is time stratigraphic, and as the McGlone below it diminishes from a maximum approaching 100 feet in the northwest to only a few feet in the southeast, northwestward downwarping is implied. Volcanic ash is known in the McGlone in only one area. The McGraw represents a time of exceptional stability, for a constant lithology continues along a trend in the Stover limestone in Pennsylvania and in the Chaumont limestone in New York and Ontario. Each is disconformably overlain, and slightly bevelled regionally, by lower Trentonian strata. There is little nondeposition in thick northwesterly sections, but there is increasing gap in the record southeastward.

The trends of differing thicknesses and lithofacies have been related to the Adirondack line (Kay, 1948, p. 1339) or the Adirondack-Tazewell axis (Woodward, 1951, p. 117), a tectonic line along the western margin of a belt of greater mobility. Changes across this line are greater than those parallel to it, particularly in the Bolarian sediments. The equivalents of these younger Bolarian beds are believed lacking in the Appalachian Valley to the east.

The lower Trentonian rocks have extremely variable facies. Their thicknesses within the region are a few hundred feet, and in the south they diminish by convergence eastward. The sediments have a striking arcuate pattern of lithologies, centering to the southwest in Virginia (Kay, 1948, p. 1413; Woodward, 1951, p. 264). Textures indicate highlands southeast of the southern part of the area from which terrigenous detritus spread in progressively finer texture, normal marine limestones prevailing on the periphery. Perhaps there were lands comparable to those in Vermont, where lower Trentonian limestones thinly veneer a gently folded and deeply eroded terrane of several thousand feet, bevelled to the Precambrian in some localities (Fowler, 1950; Thompson, 1952, p. 16).

The medial Trentonian or Denmarkian rocks are within the Martinsburg terrane, undefined upward. In the northern sections in the Western Anticlines, they are like the Salona formation, argillaceous calcilutite with shaly argillite interbeds, becoming less calcareous upward, and with few calcarenite and coquinal interbeds. Similar rocks are preserved in the westernmost exposures along the Shenandoah Valley. Farther east, the rocks are almost wholly shaly argillite; the typical Martinsburg section is in this belt. Southwestward, as at The Narrows, the so-called Martinsburg has frequent calcarenite and coquinal calcitites interbedded within denser limestones and shaly argillites. Throughout the region there are altered volcanic ash beds, but in only a few cases have

TABLE 16.—GLOSSARY OF NAMES OF MIDDLE ORDOVICIAN STRATIGRAPHIC UNITS HAVING TYPE LOCALITIES IN THE WESTERN ANTICLINES IN PENNSYLVANIA AND THE VIRGINIA AND NEAR-BY REGIONS*

Division	Lithology or Classification	Type Locality (County, State)	Author	Year	Classification
Antes	sh.	Clinton, Pa.	Kay	1943	Trentonian
Benbolt	ls.	Tazewell, Va.	Cooper and Prouty	1943	Bolarian
Ben Hur	ls.	Lee, Va.	Miller and Brosgé	1950	Trentonian
Benner	"group"	Centre, Pa.	Kay	1941	Bolarian
Blackford	"group"	Russell, Va.	Butts	1942	Chazyan, member Lurich
Botetourt	ls.	Botetourt, Va.	Cooper and Cooper	1946	Bolarian
Bowen	fm.	Tazewell, Va.	Cooper and Prouty	1943	Bolarian?
Burkes Garden	ls.	Tazewell, Va.	Cooper and Prouty	1943	Bolarian, member Benbolt
Carlim	ls.	Huntingdon, Pa.	Butts	1918	Extensive, ill-defined
Centre Hall	ls.	Centre, Pa.	Field	1918	Trentonian, member Nealmont
Chambersburg	ls.	Franklin, Pa.	Stose	1906	Extensive
Cliffield	"group"	Tazewell, Va.	Cooper and Prouty	1943	Chazyan and Bolarian
Clover	ls.	Huntingdon, Pa.	Kay	1941	Chazyan, member Loysburg
Collierstown	ls.	Rockbridge, Va.	Cooper and Cooper	1946	Trentonian
Coburn	ls.	Centre, Pa.	Field	1918	Trentonian
Curtin	ls.	Centre, Pa.	Kay	1941	Trentonian, facies Nealmont
			Rones	1955	
Dot	ls.	Lee, Va.	Miller and Brosgé	1950	Chazyan
Doylesburg	ls.	Franklin, Pa.	Craig	1949	Bolarian, member Shippensburg
Edinburg	ls.	Shenandoah, Va.	Cooper and Cooper	1946	Bolarian
Effna	ls.	Bland, Va.	Cooper	1944	Bolarian
Eggleston	fm.	Giles, Va.	Mathews	1934	Trentonian
Elway	ls.	Russell, Va.	Cooper	1951	Chazyan, member Lurich
Eyer	mem.	Huntingdon, Pa.	Kay	1944	Bolarian, member Hatter
Fannettsburg	ls.	Franklin, Pa.	Craig	1949	Bolarian, member Shippensburg
Five Oaks	ls.	Tazewell, Va.	Cooper and Prouty	1943	Chazyan, member Lurich
Gratton	ls.	Tazewell, Va.	Cooper and Prouty	1943	Bolarian
Grazier	ls.	Huntingdon, Pa.	Kay	1944	Bolarian, member Hatter
Hardy Creek	ls.	Lee, Va.	Miller and Brosgé	1950	Trentonian
Hatter	"group"	Huntingdon, Pa.	Kay	1941	Bolarian, Lower
Hostler	mem.	Huntingdon, Pa.	Kay	1944	Bolarian, member Hatter
Housum	ls.	Franklin, Pa.	Craig	1949	Trentonian, member Mercersburg

TABLE 16.—*Continued*

Division	Lithology or Classification	Type Locality (County, State)	Author	Year	Classification
Hunter	"group"	Centre, Pa.	Kay	1948	Bolarian and Trentonian
Hurricane Bridge	ls.	Lee, Va.	Miller and Brosgé	1950	Bolarian
Kaufman	ls.	Franklin, Pa.	Craig	1949	Trentonian, member Mercersburg
Lantz Mills	ls.	Shenandoah, Va.	Cooper and Cooper	1946	Bolarian, facies Edinburg
Lemont	ls.	Centre, Pa.	Butts	1918	Extensive
Liberty Hall	ls.	Rockingham, Va.	Campbell	1905	Bolarian, facies Edinburg
Lincolnshire	ls.	Tazewell, Va.	Cooper and Prouty	1943	Chazyan
Loysburg	fm.	Bedford, Pa.	Field	1918	Chazyan
Lurich	fm.	Giles, Va.	Kay	new	Chazyan
McGlone	ls.	Monroe, W. Va.	Kay	new	Bolarian
McGraw	ls.	Alleghany, Va.	Kay	new	Bolarian
Martin Creek	ls.	Lee, Va.	Miller and Brosgé	1950	Bolarian ?
Martinsburg	sh.	Jefferson, W. Va.	Geiger and Keith	1891	Trentonian
Mercersburg	ls.	Franklin, Pa.	Craig	1942	Trentonian
Moccasin	fm.	Scott, Va.	Campbell	1894	Trentonian
Murat	ls.	Rockbridge, Va.	Campbell	1905	Chazyan Lincolnshire
Nealmont	ls.	Huntingdon, Pa.	Kay	1941	Trentonian
New Market	ls.	Shenandoah, Va.	Cooper and Cooper	1946	Chazyan
Oak Hall	ls.	Centre, Pa.	Kay	1941	Trentonian, member Nealmont
Onego	ls.	Pendleton, W. Va.	Kay	new	Trentonian, member Salona
Oranda	fm.	Shenandoah, Va.	Cooper and Cooper	1946	Trentonian
Peery	ls.	Tazewell, Va.	Cooper and Prouty	1943	Bolarian
Poteet	ls.	Lee, Va.	Miller and Brosgé	1950	Chazyan
Pinesburg	ls.	Washington, Md.	Craig	1949	Bolarian, member Shippensburg
Rob Camp	ls.	Lee, Va.	Miller and Brosgé	1950	Chazyan
Rockwell	ls.	Russell, Va.	Cooper	1951	Bolarian
Rodman	ls.	Blair, Va.	Butts	1918	Trentonian, member Nealmont
Row Park	ls.	Washington, Md.	Neumann	1951	Chazyan
Saint Luke	ls.	Shenandoah, Va.	Cooper and Cooper	1946	Trentonian
Saint Paul	"group"	Washington, Md.	Neumann	1951	Chazyan
Salona	ls.	Clinton, Pa.	Field	1919	Trentonian
Shannondale	ls.	Tazewell, Va.	Cooper and Prouty	1943	Bolarian, member Benbolt
Shippensburg	ls.	Cumberland, Pa.	Craig	1942	Bolarian
Snyder	ls.	Huntingdon, Pa.	Kay	1941	Bolarian
Stallard	ls.	Lee, Va.	Cooper	1950	Unpublished; about Ben Hur
Stover	ls.	Huntingdon, Pa.	Kay	1941	Bolarian
Strasburg	ls.	Shenandoah, Va.	Ulrich	1930	Ill-defined Cooper and Cooper, 1946

TABLE 16.—*Continued*

Division	Lithology or Classification	Type Locality (County, State)	Author	Year	Classification
Thompson Valley	ls.	Tazewell, Va.	Prouty	1946	Bolarian
Tumbez	ls.	Russell, Va.	Cooper	1951	Chazyan
Valentine	ls.	Centre, Pa.	Field	1919	Trentonian, member Curtin
Valley View	ls.	Centre, Pa.	Kay	1943	Trentonian, member Curtin
Ward Cove	ls.	Tazewell, Va.	Cooper and Prouty	1943	Bolarian
Wardell	ls.	Tazewell, Va.	Cooper and Prouty	1943	Bolarian
Witten	ls.	Tazewell, Va.	Cooper and Prouty	1943	Bolarian
Woodway	ls.	Lee, Va.	Miller and Brosgé	1950	Bolarian
Whistle Creek	ls.	Rockbridge, Va.	Cooper and Cooper	1946	Chazyan

* References prior to 1935 in Wilmarth (1938). A similar glossary of units in New York and Ontario is in Kay (1937, p. 296–297). Lithologic abbreviations: fm.—formation; ls.—limestone; sh.—shale.

these been useful in correlation within this region, though they are exceptionally valuable in Pennsylvania. The upper limit of the Denmarkian has not been ascertained; there has been little study of the poorly exposed shaly sediments.

There was a source of terrigenous sediments southward and eastward during Denmarkian time. Disturbance was not initiated during Denmarkian time, though, unlike the New York-Vermont region, for the Nealmontian is also coarser terrigenous to the south, and the Blountian Disturbance of the earlier Bolarian had produced coarse terrigenous rocks in the southwestern part of the area along its southeastern margin.

In summary, the region was one of almost continuous epeirogeny through Chazyan, Bolarian, and Trentonian epochs, but the pattern of deformation changed several times. In the earlier history, culminating in the early Bolarian, regional tilting into a shallow miogeosyncline on the southeast was complemented by rising lands on the southeast that produced terrigenous sediment. Then came a stage of relative stability with shallow-laid late Bolarian forming northwestwardly thickening calcitites in northwestern belts. With some rejuvenation of the southeastern lands, a trough southwest of the area received terrigenous sediments, considerably red. Study of medial Ordovician rocks from the Adirondack region through Pennsylvania into the Virginias reveals the changing forms of this belt bordering the more mobile geosyncline to the southeast, but shows also that this deformation changed in time and nature along the belt.

REFERENCES CITED

Bassler, R. S., 1950, Faunal lists and descriptions of Paleozoic corals: Geol. Soc. America Mem. 44, 137 p.

Butts, Charles, 1942, Geology of the Appalachian Valley of Virginia: Va. Geol. Survey Bull. 52 (1940), pt. 1, 568 p.

Craig, L. C., 1949, Lower Middle Ordovician of south-central Pennsylvania: Geol. Soc. America Bull., v. 60, 707–799.

Cooper, B. N., 1944a, Geology and mineral resources of the Burkes Garden quadrangle, Virginia: Va. Geol. Survey Bull. 69, 299 p.

—— 1944b, Industrial limestones and dolomites in Virginia, New River-Roanoke River district: Va. Geol. Survey Bull. 62, 98 p.

—— 1950, Kentucky Geological Society, 1950 field excursion in southwestern Virginia, May 5, 6, 7, privately reproduced.

—— 1951, Industrial limestones and dolomites in Virginia, Clinch Valley district: Va. Geol. Survey Bull. 66 (1945), 259 p.

—— 1953, Trilobites from the lower Champlainian formations of the Appalachian Valley: Geol. Soc. American Mem. 55, 69 p.

Cooper, B. N., and Cooper, G. A., 1946, Lower Middle Ordovician stratigraphy of the Shenandoah Valley, Virginia: Geol. Soc. America Bull., v. 57, p. 1140–1191.

Cooper, B. N., and Prouty, C. E., 1943, Stratigraphy of the Lower Middle Ordovician of Tazewell County, Virginia: Geol. Soc. America Bull., v. 54, p. 819–886.

Field, R. N., 1919, The Middle Ordovician of central and south-central Pennsylvania: Am. Jour. Sci., 4th ser., v. 48, p. 403–428.

Gawler, Phillip, 1950, Stratigraphy and structure

of the Castleton area, Vermont: Vt. Geol. Survey Bull. 2, 83 p.

Geiger, H. R., and Keith, Arthur, 1891, The structure of the Blue Ridge near Harper's Ferry: Geol. Soc. America Bull., v. 2, p. 155–164.

Johnston, W. A., 1911, Simcoe District, Ontario: Canada Geol. Survey Summary Rept. for 1910, p. 188–192.

—— 1912, Geology of Lake Simcoe Area, Ontario, Brechin and Kirkfield sheets: Canada Geol. Survey Summary Rept. for 1911, p. 253–261.

Kay, Marshall, 1937, Stratigraphy of the Trenton Group: Geol. Soc. America Bull., v. 48, p. 233–302.

—— 1941, Middle Ordovician formations in central Pennsylvania (Abstract): Geol. Soc. America Bull., v. 52, p. 1969.

—— 1942a, Ottawa-Bonnechere graben and Lake Ontario homocline: Geol. Soc. America Bull., v. 53, p. 585–646.

—— 1942b, Development of the Allegheny synclinorium and adjoining region: Geol. Soc. America Bull., v. 53, p. 1601–1658.

—— 1943, Chemical lime in Central Pennsylvania: Econ. Geology, v. 38, p. 188–203.

—— 1944, Middle Ordovician of Central Pennsylvania: Jour. Geology, v. 52, p. 1–24, 97–116.

—— 1945, Highgate Springs Sequence, northwestern Vermont and southeastern Quebec (Abstract): Geol. Soc. America Bull., v. 56, p. 1171–1172.

—— 1947, Bolarian Series of the Ordovician (Abstract): Geol. Soc. America Bull., v. 58, p. 1198–1199.

—— 1948, Summary of Middle Ordovician bordering Allegheny synclinorium: Am. Assoc. Petroleum Geologists Bull., v. 32, p. 1397–1416.

—— 1953, Geology of the Utica quadrangle, New York: N. Y. State Mus. Bull. 347, 126 p.

Liberty, B. A., 1955, Stratigraphic studies of the Ordovician System in central Ontario: Geol. Assoc. Canada, v. 7, p. 139–147.

McCartney, E. S., 1953, Recurrent maladies in scholarly writing: Ann Arbor, Univ. Mich. Press, 142 p.

Miller, R. L., and Brosgé, W. P., 1950, Geology of the Jonesville district, Lee County, Virginia: U.S. Geol. Survey Oil and Gas Inv. Prelim. map 104.

—— 1954, Geology and oil resources of the Jonesville district, Lee County, Virginia: U.S. Geol. Survey Bull. 990, 240 p.

Moore, R. C., 1949, Introduction to Historical Geology: New York, McGraw-Hill, 582 p.

Neuman, R. B., 1951, St. Paul group: revision of the "Stones River" group of Maryland and adjacent states: Geol. Soc. America Bull., v. 62, p. 267–324.

Okulitch, V. J., 1939, The Ordovician section at Coboconk, Ontario: Roy. Canad. Inst. Trans., v. 22, p. 319–339.

Oxley, Philip, 1951, Chazyan reef facies relationships in the northern Champlain Valley: Denison Univ. Bull., Jour. Sci. Lab., v. 42, p. 92–111.

Prouty, C. E., 1946, Lower Middle Ordovician of southwest Virginia and northeast Tennessee: Am. Assoc. Petroleum Geologists Bull., v. 30, p. 1140–1191.

Rosenkrans, R. R., 1936, Stratigraphy of Ordovician bentonite beds in southwestern Virginia: Va. Geol. Survey Bull. 46, p. 85–112.

Sinclair, G. W., 1954, The age of the Kirkfield formation in Ontario: Ohio Jour. Sci., v. 54, p. 31–41.

Thompson, J. B., Jr., 1952, Southern Vermont, Guidebook for field trips in New England: Geol. Soc. America, p. 14–23.

Twenhofel, W. H., *et al.*, 1954, Correlation of the Ordovician formations of North America: Geol. Soc. America Bull., v. 65, p. 247–298.

Ulrich, E. O., Foerste, A. F., Miller, A. K., and Unklesbay, A. G., 1944, Ozarkian and Canadian cephalopods, pt. III: Longicones and summary: Geol. Soc. America Spec. Paper 58, 226 p.

Whittington, H. B., and Evitt, W. R., II, 1953, Silicified Middle Ordovician trilobites: Geol. Soc. America Mem. 59, 315 p.

Wilmarth, M. G., 1938, Lexicon of geologic names of the United States: U. S. Geol. Survey Bull. 896, 2296 p.

Wilson, A. E., 1946, Geology of the Ottawa-St. Lawrence Lowland, Ontario and Quebec: Geol. Survey Canada Mem. 241, 65 p.

Woodward, H. P., 1932, Geology and mineral resources of the Roanoke area, Virginia: Va. Geol. Survey Bull. 34, 172 p.

——1951, Ordovician System of West Virginia: W. Va. Geol. Survey, v. 21, 627 p.

Young, F. P., Jr., 1943, Black River stratigraphy and faunas: Am. Jour. Sci., v. 241, p. 141–166, 209–240.

COLUMBIA UNIVERSITY, N. Y.

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, FEBRUARY 23, 1954
PROJECT GRANT 475/45

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 67, PP. 107–112, 2 PLS. JANUARY 1956

POST-LARAMIE STRATIGRAPHIC CORRELATIONS IN THE DENVER BASIN, COLORADO

BY STANLEY O. REICHERT

ABSTRACT

In mapping and correlating post-Laramie formations in the Denver Basin, clear-cut mappable formation boundaries have been defined and used.

It is proposed that

(1) the Laramie-Arapahoe contact remain as originally defined by Emmons, Cross, and Eldridge (1896);

(2) the Arapahoe-Denver contact be placed at the widespread erosional disconformity at the base of the lowest, thickest, and most prominent basalt-andesite pebble conglomerate bed in the Denver area, instead of at the first appearance of andesitic debris as originally proposed by Emmons, Cross, and Eldridge (1896).

The following changes in nomenclature are proposed:

(1) The Arapahoe and Denver formations can be mapped throughout the Denver Basin, and these names should replace the term "lower Dawson" of Dane and Pierce (1936).

(2) "Dawson formation" (type section at Dawson Butte) should designate only "upper Dawson" of Dane and Pierce.

(3) The name "Green Mountain conglomerate" should be abandoned as it is only a partial representative of the proposed Dawson formation as restricted in (2).

(4) The Laramie formation should be restricted to its original definition by Emmons, Cross, and Eldridge (1896) rather than extended as proposed by Brown (1943).

CONTENTS

TEXT

	Page
Introduction	107
Formations involved	108
Summary of methods and results	108
Conclusions and proposed changes in nomenclature	110
Bibliography	111

ILLUSTRATIONS

Plate	Facing page
1. Post-Laramie correlation map of the Denver Basin, Colorado	107
2. Post-Laramie correlation of stratigraphic columns in the Denver Basin, Colorado	112

TABLE

Table	Page
1. Comparison of thicknesses of post-Laramie sediments, Green Mountain area, Jefferson County, Colorado	108

INTRODUCTION

The purpose of the present paper is to review the post-Laramie stratigraphy of the Denver Basin and show that clear-cut mappable boundaries between formations can be selected over the entire area. Lithologic characteristics are the basis for the designation of formations. A revision of the nomenclature is proposed.

From 1946 to 1955 the writer worked intermittently on detailed mapping of the Golden-Green Mountain area (Reichert, 1954, Pls. 2, 3) and on reconnaissance mapping of the post-Laramie sediments along the perimeter of the Denver Basin. The small-scale (1 inch = 2 miles) mapping done directly on the U. S. Geological Survey topographic sheets has been transcribed onto a base map of the Denver Basin which was traced from the U. S. Geo-

TABLE 1.—COMPARISON OF THICKNESSES OF POST-LARAMIE SEDIMENTS, GREEN MOUNTAIN AREA, JEFFERSON COUNTY, COLORADO

Formation	Thickness (in feet) according to:			
	Reichert	Emmons, Cross, Eldridge (1896, Pl. 5)	Marr (1929, Colo. School of Mines, Unpub. Rept., p. 11)	
			Min.	Max.
Green Mountain conglomerate	423	525	590	610
Denver	434	915	293	323
	1125	1715	966	1067
Arapahoe	691	800	673	744
Total post-Laramie thickness	1548	2240	1556	1677

logical Survey 1935 geological map of Colorado. Plates 1 and 2 show the results of this work and the correlations proposed.

FORMATIONS INVOLVED

This paper is concerned only with the post-Laramie formations in the Denver Basin shown on Plates 1 and 2. In the northern part of the area the U. S. Geological Survey recognizes the Arapahoe as the older and the Denver as the younger formation. In the Castle Rock area and southward, these same formations have long been designated as lower Dawson and upper Dawson, but exact correlations had not yet been established when the 1935 geological map of Colorado was published, and no attempt was made on the Colorado map to differentiate any of the post-Laramie sediments except the Castle Rock conglomerate.

SUMMARY OF METHODS AND RESULTS

In using a semicontrolled aerial-photograph mosaic on the scale of 8 inches to 1 mile for the field mapping of the Golden-Green Mountain area in Jefferson County, Colorado, the writer found discrepancies in the total thickness of all post-Laramie formations as well as in individual formation thicknesses (Table 1).

Thicknesses in Table 1 were obtained by measuring the same section exposed along the west side of Green Mountain, SW¼ Sec. 13, T. 4 S., R. 70 W. Care was taken to select the same stratum, as nearly as could be determined from Cross' or Marr's description, for the boundary in each case.

There is disagreement for each individual formation thickness wherever the lithologic horizon is uncertain.

The writer chose prominent lithologic breaks which could be traced over the entire large-scale aerial-photograph mosaic of the Golden-Green Mountain area (Reichert, 1954, Pl. 3). The base of the Arapahoe formation as defined by Emmons, Cross, and Eldridge (1896, p. 154) is marked by an arkosic conglomerate 100 feet thick. It is easily traced on the mosaic and in the field. The base of the Denver formation was placed by Emmons, Cross, and Eldridge (1896, p. 160) at the first appearance of andesitic debris. This horizon varies and cannot be delineated on the large-scale mosaic nor on the ground. It is unmappable and has led to great confusion throughout the Denver Basin. The writer chose the base of the lowest, thickest, and most prominent basalt-andesite pebble-conglomerate bed as the base of the Denver formation. This bed can be traced on the aerial-photograph mosaic of the Golden-Green Mountain area. Finlay (1916) mapped this horizon in the Colorado Springs folio as the Tda unit of the Dawson arkose, and the writer traced it for 10 miles along the strike of the beds in the Castle Rock quadrangle (Pl. 1).

The base of the Green Mountain formation as defined by Hares (1926, p. 175) and Marr (1929, Colo. School Mines Unpub. Rept., p. 10–13) is marked by an erosional disconformity overlain by a basal andesite- and basalt-pebble conglomerate 50–150 feet thick, which is easily traced in the field and on the large-scale mosaic. The proportion of basic lava detritus decreases rapidly up section, being replaced by ever-

increasing quantities of boulders of Precambrian granites, gneisses, schists, quartzites, and sandstones toward the top of the Green Mountain conglomerate. The lower basalt-andesite pebble member of the Green Mountain conglomerate thins and disappears southeastward. Southeast of Littleton in T. 6 S., R. 68 W., the basal part of the so-called Monument Creek formation is an arkosic sandstone and conglomerate, 50 feet thick, very similar lithologically to the basal part of the upper member of the Green Mountain conglomerate on Green Mountain, except that the conglomerate becomes finer-grained southeastward. Ten miles due south, in Sec. 20, T. 7 S., R. 68 W., this same 50-foot arkosic sandstone and conglomerate is overlain by a 50-foot sandy, carbonaceous shale containing abundant fossil plants. These two beds are correlated with beds 7 and 8, respectively, of R. W. Brown's (1943, p. 73) section at the Douglas (Lehigh) Coal Mine. Yet here these beds belong to the upper Dawson formation; south of Littleton they are called Monument Creek formation, and on Green Mountain they are called Green Mountain conglomerate (Pls. 1, 2).

Before the boundaries were drawn for the post-Laramie formations (Pl. 1), the location, geologic age, and lithologic characteristics of every place where plant or animal fossils had been collected were plotted on the map. Next, the Denver-Monument Creek boundary, as given by Emmons *et al.* (1896, Pl. 2), was transcribed to Plate 1 as a solid line from Scranton to 6 miles north of Sedalia. The lower Dawson-upper Dawson contact, as mapped by Dane and Pierce (1936, p. 1314–1315), was drawn as a solid line from 8 miles southeast of Falcon to 13 miles west of Bland. The basal Dawson Tda unit, as mapped by Finlay (1916, geologic map), was next drawn as a solid line from 3 miles west of Drennan to 3 miles northwest of Pikeview. The continuation of this Tda unit, as mapped by the writer in 1954 along the unfaulted Laramie-lower Dawson contact from 5 miles west of Larkspur Butte to 5 miles northwest of Dawson Butte, was plotted next on Plate 1. The Arapahoe-Denver contact, as redefined in this paper, was traced from 4 miles northeast of Morrison to 4 miles southwest of Sedalia, where it is faulted out. Similarly, the Monument Creek-Denver contact was traced, intermittently, from 6 miles north of Sedalia to 8 miles southeast of Falcon. This Denver-Monument Creek or lower Dawson-upper Dawson contact is shown on Plate 1 as a broken line so as to distinguish it from its solid-line continuation, which had been mapped by earlier workers. Lastly, R. W. Brown's Cretaceous-Tertiary time line (Brown, 1943, p. 67) was transcribed to Plate 1.

Plate 2 shows four measured stratigraphic sections (1, 2, 3, and 4) corresponding to the numbers on Plate 1. The following horizons, from older to younger, were used to establish correlations:

(1) The erosional disconformity separating the basal Arapahoe arkosic conglomerate from the underlying Laramie clays

(2) The erosional disconformity between the base of the basal andesite-basalt-pebble conglomerate and the underlying light-colored arkosic, sandy shales of the Arapahoe formation (This disconformity marks the base of the redefined Denver formation of this paper and is correlated with the disconformity at the base of the Tda unit of the lower Dawson arkose, shown on the stratigraphic sections at Castle Rock, Colorado Springs, and Calhan.)

(3) R. W. Brown's Cretaceous-Tertiary time line

(4) The prominent erosional disconformity between the base of the light-colored arkosic sandstones and conglomerates of the upper Dawson and the underlying darker-colored graywacke, andesitic, micaceous, carbonaceous sandstones and shales of the lower Dawson (In the northwestern part of the Denver Basin this horizon is the Green Mountain-Denver or the Monument Creek-Denver boundary.)

(5) R. W. Brown's Paleocene plant horizon

Using these five horizons for correlation the following facts are noted and mapped:

(1) The Arapahoe formation is thickest in the Golden-Green Mountain area. The source of these clastics is thought to have been the rising Front Range in late Cretaceous time. The Arapahoe thins and becomes finer-grained to the east, south, and southeast. Only the basal conglomerate or coarse arkosic sandstone is found east and southeast of the Castle Rock quadrangle, where it ranges from 0 to 35 feet

thick in the Castle Rock and Colorado Springs areas, and from 50 to 100 feet thick in the Matheson-Bland-Byers areas. This basal sandstone and conglomerate characteristically contains small pebbles of black, red, and yellow chert, white limestone, and granite in a matrix of coarse arkosic yellow sandstone. The outcrop width of this bed (Ka) is too small to map to scale along the southwest and east edges of the Denver Basin, so is exaggerated in Plate 1.

(2) The Denver formation is also most characteristically developed in the Denver-Golden-Green Mountain area, where it is typically composed of andesitic and basaltic sandstones, shales, and conglomerates. Like the Arapahoe, it changes composition and becomes finer-grained eastward and southeastward away from the Front Range volcanic area. The basal conglomerate (Tda) member in the Golden-Green Mountain area can be traced as an andesitic sandstone bed overlying the light-colored Arapahoe in the Castle Rock and Colorado Springs areas. This same bed is believed to occur as a dark-green and brown graywacke sandstone and shale (Tda) in the Matheson-Bland-Byers areas. The dark color and abundant detrital hornblende, biotite, augite, and plagioclase established its correlation with the Tda member of the Denver formation in the Denver-Castle Rock-Colorado Springs areas. Lithologically it is quite distinct from the light-colored arkosic sandstone and shale of the Arapahoe. The Tda member of the Denver formation varies from a 10-foot andesite-basalt pebble conglomerate in the Golden area, to a 30-foot andesitic sandstone in the Castle Rock area, to a 90-foot andesitic sandstone in the Colorado Springs area, to a 10–50-foot dark graywacke sandstone and shale in the southeastern and eastern parts of the Denver Basin. Its outcrop width on Plate 1 is, therefore, exaggerated.

(3) The Dawson arkose as originally described and defined by Richardson (1915, p. 7–14) attains a maximum thickness of about 2000 feet in the Castle Rock quadrangle. This section was remeasured by the writer and is shown as column 2 on Plate 2. The lower 1200 feet from the basal Arapahoe conglomerate to above the Paleocene plant horizon was measured in Section 30, T. 7 S., R. 68 W., 4 miles west of Sedalia, near Brown's (1943, p. 73) measured section. A complete section of the Dawson arkose from the Laramie-Arapahoe contact up to the rhyolite lava flow capping Dawson Butte was measured in Sections 1 and 12, T. 9 S., R. 68 W. (Photographs of these rocks in the Dawson Butte area are shown in Reichert, 1954, p. 18, 20, 48.) The type section of the upper Dawson of Dane and Pierce (1936, p. 1320–1325) is shown as column 2 of Plate 2, and the type locality of the upper Dawson is on the west flank of Dawson Butte in the Castle Rock quadrangle.

Conclusions and Proposed Changes in Nomenclature

(1) The Arapahoe formation is the lithologic and time equivalent of the basal part of the lower Dawson of Dane and Pierce in the southeast part of the Denver Basin. Only the basal conglomerate or coarse arkosic sandstone is found throughout the Denver Basin. Since an erosional disconformity everywhere separates the Arapahoe from the overlying (Tda) basal member of the Denver formation, variations in the original thickness of the Arapahoe and pre-Denver erosion account for the great variation in the thickness of the Arapahoe. The Arapahoe formation throughout the Denver Basin should include all Cretaceous light-colored arkosic conglomerates, sandstones, and shales from the unconformity at the top of the Laramie up to the dark andesitic or graywacke conglomerates, sandstones, and shales of the Tda member of the Denver formation as defined and mapped in this paper. Therefore, it is proposed that the term Arapahoe be extended to cover the basal conglomerate (or remnants of the basal Arapahoe conglomerate) throughout the Denver Basin as shown in Plates 1 and 2.

(2) The Denver formation is the lithologic and time equivalent of that portion of the lower Dawson of Dane and Pierce in the southeast part of the Denver Basin extending from the base of the Tda unit up to the widespread erosional disconformity, which is marked by the abrupt change from dark graywacke, carbonaceous sandstones, and shales to light-gray, coarse-arkosic sandstones and conglomerates. As seen in Plates 1 and 2, Brown's Cretaceous-Paleocene paleontologic time line varies in

stratigraphic position with respect to the base and top of the Denver formation. It is proposed that the Denver formation be extended throughout the Denver Basin to include all dark clastic sediments derived from the erosion of basic lavas as indicated by their mineral composition, which is in strong contrast to the light-colored arkosic sediments in the underlying Arapahoe and the overlying upper Dawson of Dane and Pierce. Plates 1 and 2 show the Arapahoe and Denver formations as extended, with the elimination of the term "lower Dawson" of Dane and Pierce.

(3) Since the Green Mountain conglomerate is only a partial representative of the type section of the upper Dawson, as are also the upper Dawson sediments in the Colorado Springs and Calhan areas, it is proposed that the terms "lower Dawson" and "upper Dawson" of Dane and Pierce and "Green Mountain conglomerate" of Hares (1926, p. 175) be eliminated and be replaced throughout the Denver Basin by Arapahoe, Denver, and Dawson formations as shown in Plates 1 and 2.

(4) The Tda basal member of the Denver formation is shown as a separate unit on Plates 1 and 2, mainly to establish the stratigraphic correlations, but a revised geological map of Colorado need not make this distinction.

(5) In view of the limits set for the Arapahoe, Denver, and Dawson formations, the Laramie formation should be restricted to its original definition and usage by Emmons, Cross, and Eldridge (1896, p. 72–77).

(6) A thick section of post-Laramie clastics was deposited during a short period of time, and tectonic conditions fluctuated rapidly causing large differences in lithology and widespread erosional disconformities.

(7) Paleontologic time lines diverge from formation boundaries because of the complex tectonic control of sedimentation in the Denver Basin in post-Laramie time.

Bibliography

Brown, R. W., 1943, Cretaceous-Tertiary boundary in the Denver Basin, Colorado: Geol. Soc. America Bull., v. 54, p. 65–86.

Dane, C. H., and Pierce, W. G., 1936, Dawson and Laramie formations in southeastern part of Denver Basin, Colorado: Am. Assoc. Petroleum Geologists Bull., v. 20, p. 1308–1328.

Emmons, S. F., Cross, C. W., and Eldridge, G. H., 1896, Geology of the Denver Basin: U. S. Geol. Survey Mon. 27, p. 1–556.

Finlay, G. I., 1916, Description of the Colorado Springs quadrangle, Colorado: U. S. Geol. Survey, folio 203.

Hares, C. J., 1926, What is the Denver formation? (Abstract): Geol. Soc. America Bull., v. 37, p. 175.

Lavington, C. S., 1941, Is there an unconformity between the Denver formation and the Dawson arkose? Paper presented before Rocky Mountain Assoc. of Geologists.

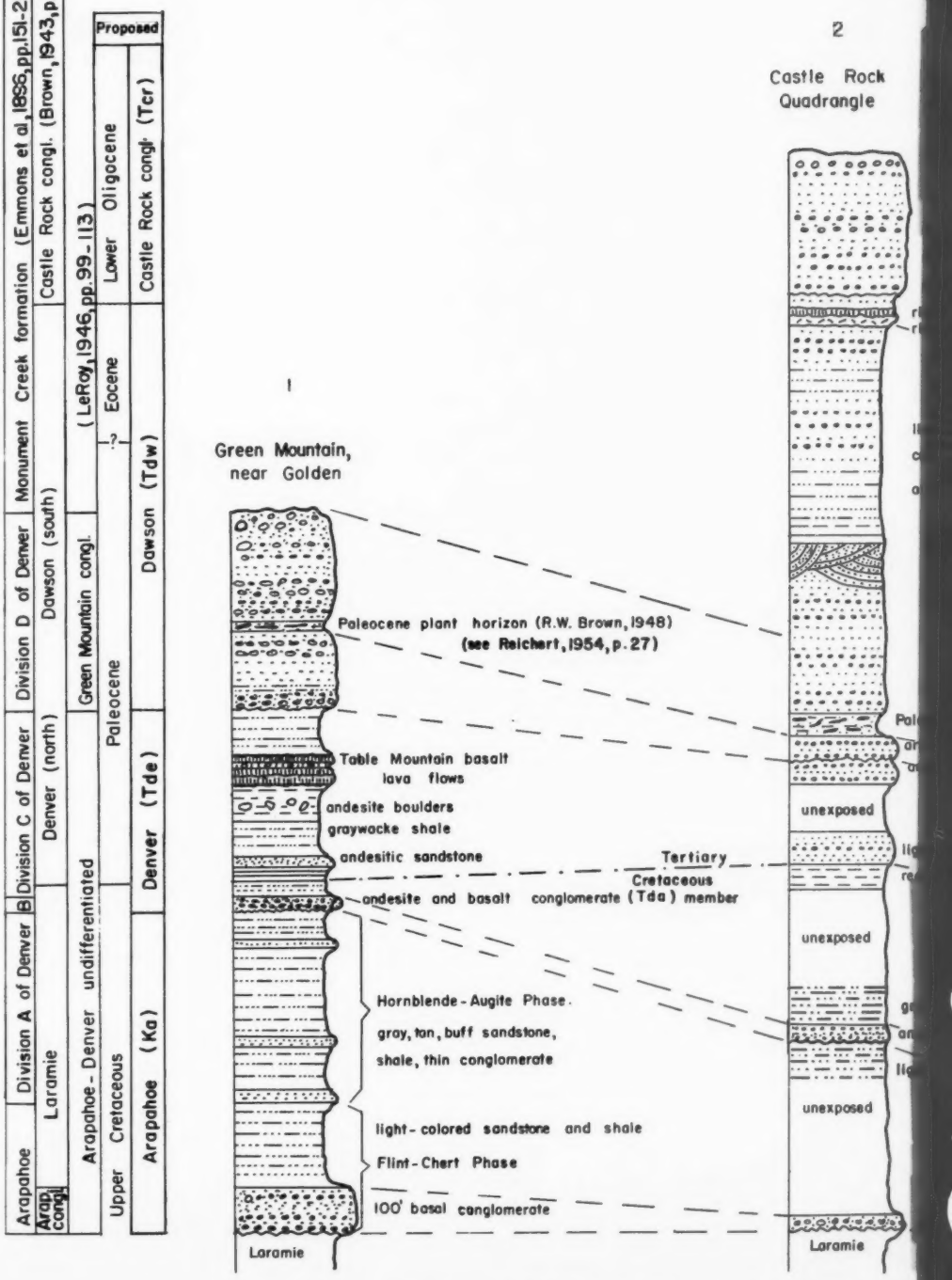
LeRoy, L. W., 1946, Stratigraphy of the Golden-Morrison area, Jefferson County, Colorado: Colo. School Mines Quart., v. 41, no. 2, p. 1–115.

Reichert, S. O., 1954, Geology of the Golden-Green Mountain area, Jefferson County, Colorado: Colo. School Mines Quart., v. 49, no. 1, p. 1–96.

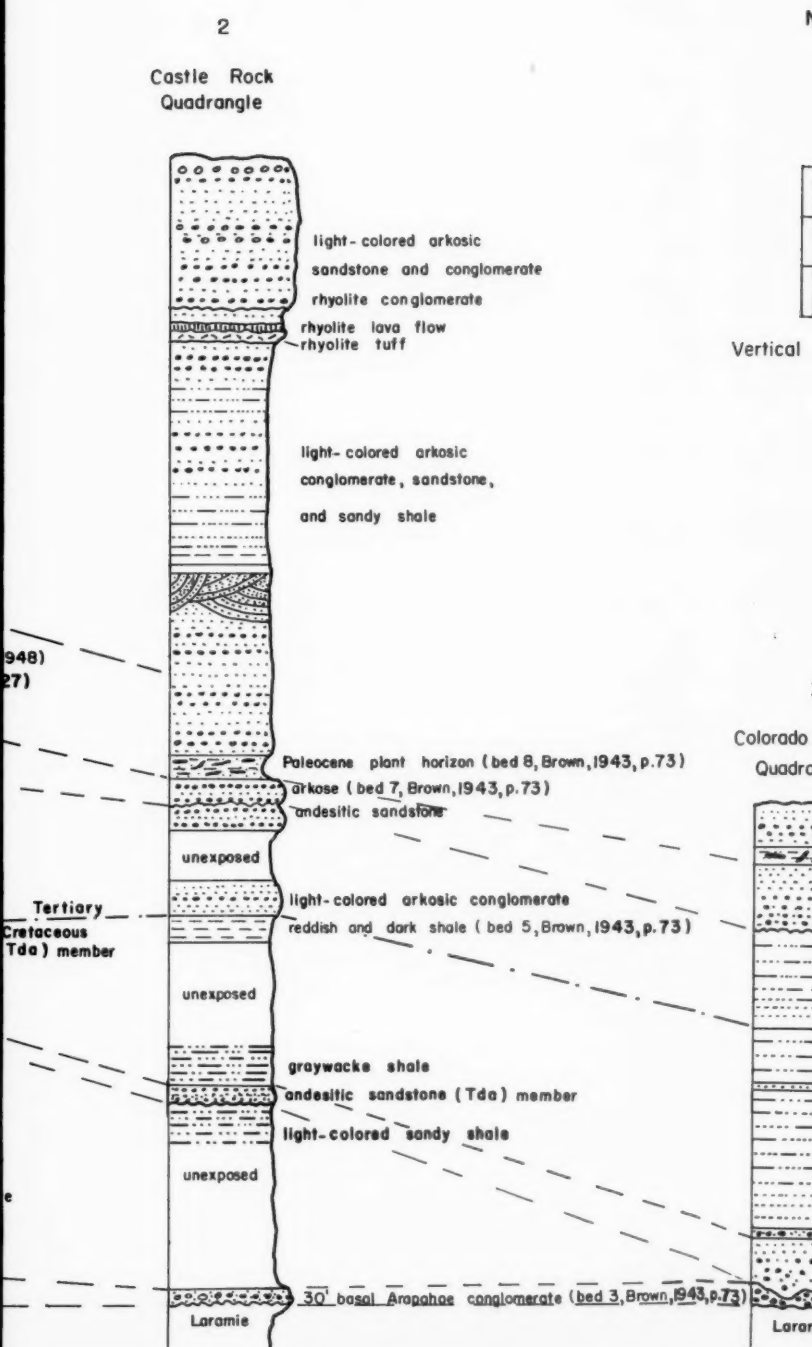
Richardson, G. B., 1915, Description of the Castle Rock quadrangle, Colorado: U. S. Geol. Survey, folio 198.

Louisiana State University, Baton Rouge, La.

Manuscript Received by the Secretary of the Society March 10, 1955

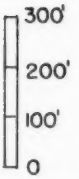


POST-LARAMIE CORRELATION OF



CORRELATION OF STRATIGRAPHIC COLUMNS IN

Note: See Plate I for map locations.



Vertical Scale

Correlation by Stanley O. Reichert

Southeast of Denver near

3

Colorado Springs Quadrangle

Paleocene plant horizon (Brown, 1943, p. 77) near Falcon.

light-colored arkosic sandstone and conglomerate. caprock at Corral Bluffs

light-colored sandstone and shale containing Paleocene mammals (Brown, 1943, p. 76)

andesitic sandstone and shale containing dinosaur bones (Brown, 1943, p. 76)

20' conglomerate composed of granite, schist

90' basal Denver andesitic sandstone (Tda) member

0-35' basal Arapahoe conglomerate (Finlay, 1916, p. 9)

p. 73)

Laramie

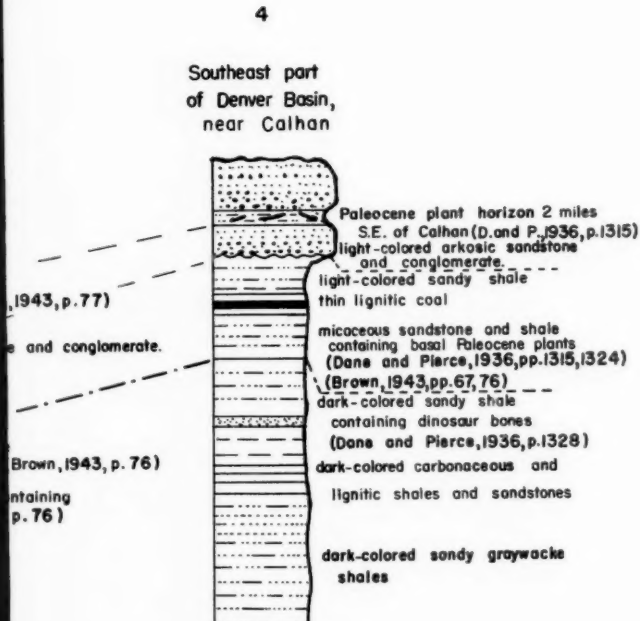
La

NS IN THE DENVER BASIN, COLORADO

ons.

n by Stanley O. Reichert 1955

4


Southeast part
of Denver Basin,
near Calhan
Paleocene plant horizon 2 miles S.E. of Calhan (D. and P., 1936, p. 1315)
light-colored arkosic sandstone and conglomerate.
light-colored sandy shale
thin lignitic coal
micaceous sandstone and shale containing basal Paleocene plants
(Dane and Pierce, 1936, pp. 1315, 1324)
(Brown, 1943, pp. 67, 76)
dark-colored sandy shale containing dinosaur bones
(Dane and Pierce, 1936, p. 1328)
dark-colored carbonaceous and lignitic shales and sandstones
dark-colored sandy graywacke shales
dark-colored arkosic sandstone
graywacke sandstone and shale (Tda) member
100' basal Arapahoe sandstone and conglomerate, (Ka)
(Dane and Pierce, 1936, p. 1321)
Laramie
,1943, p. 77)
e and conglomerate.
Brown, 1943, p. 76)
ntaining
p. 76)
ranite, schist
tone (Tda)
ate (Finlay, 1916, p. 9)

N. COLORADO

SHORT NOTES

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 67, PP. 113–120 JANUARY 1956

UNITED NATIONS CONFERENCE ON THE PEACEFUL USES OF ATOMIC ENERGY: GEOLOGICAL ASPECTS

By PAUL F. KERR

The natural occurrence of uranium and thorium was one of a large number of subjects on the agenda of the United Nations Conference on the Peaceful Uses of Atomic Energy held in Geneva, Switzerland, August 8–20, 1955. As a United Nations representative to the Conference, the writer was asked to prepare a summary of the submitted geologic papers co-ordinated with the current literature, and to organize an international discussion panel. Although this summary has been published in preliminary form (Conference Paper 1114), a review of the geologically salient features of the Conference as well as of several items which merit special emphasis appears worthy of the attention of the Society.

These conference papers constitute the most extensive assembly of contributions on the various phases of atomic energy which has been made public. They will be combined in final form as one volume in a set of 16 volumes which will be distributed by the United Nations in January 1956. A few papers were withdrawn or have not been translated yet, but almost 1100 conference papers are available in preliminary form. They have been printed as submitted by the respective authors and as cleared by the various delegations.

The papers which were published individually for the conference are available for public distribution by the Sales and Circulation Section of the United Nations, New York. However, because of the wide distribution, papers must be ordered by the number given in the published Index of Abstracts. The price of each paper is 25 cents.

Twenty-four nations submitted 115 papers devoted to the general field of uranium and thorium geology, geophysics, mineral relationships, and exploration. Of these, 85 papers were submitted by the United States delegation. It is understood that a complete set of the United States papers submitted to the Conference is being prepared for publication by the U. S. Geological Survey.

The Canadian delegation submitted a comprehensive set of publications which were selected from their recent technical literature. The U.S.S.R. presented several papers on geophysical and geochemical exploration. The Belgian delegation's contribution gives detailed geological and mineralogical data based on the last 10 years of exploration at the Shinkolobwe uranium mine in the Belgian Congo.

In addition to the submitted papers, representatives of 12 nations participated in a panel discussion on features of geological occurrence. The nations represented include Argentina, Australia, Belgium, Brazil, Canada, France, India, Italy, Japan, Portugal, the United Kingdom, and the United States.

Exhibits devoted mainly to uranium deposits and their mineralogy were presented by the U.S.S.R., France, Belgium, and the United States. These included a slab of vein uraninite from the U.S.S.R. which was almost 3 square feet in area with a botryoidal crust several inches thick. A comprehensive set of specimens and illustrations outlined the vein relationships in the French Massif Central. A rough cube from the Belgian Congo which measured about 2 feet on each side and consisted almost entirely of uraninite was in the commercial exhibit of the Union Minière. Data on the Canadian geological occurrences of uranium were co-ordinated with other features in the Canadian exhibit.

Many of the geological data in the conference

contributions are applicable not only to the study of uranium and thorium occurrences but also to those of other metals. The various types of occurrence are outlined in detail, and in many instances observations on their origin are included. Several occurrences are described comprehensively for the first time in the literature.

Among the most significant of the recent United States discoveries is the high-grade lignitic ore of northwestern South Dakota. The figures released indicate that these deposits are of substantial magnitude. However, their origin is not established. Denson and Gill (Conference Paper 57) suggest that the uranium in the lignite may be explained by the "ash-leach" theory in which the ore metal is derived from overlying deposits of volcanic ash. King (Conference Paper 286) favors an original emplacement of uranium ions from underlying sources, possibly by hydrothermal solutions.

The papers on Canadian uranium deposits submitted to the Conference as well as panel discussion indicate large reserves in the Blind River area. The unusual uranium mineral brannerite, along with uraninite and thucholite, is disseminated through conglomerate and associated sediment of the Mississagi quartzite. The ores are low grade but are widespread. The deposit is similar in many respects to that in the Witwatersrand conglomerate. However, gold is only a minor associate at Blind River. Dr. Elysiario Távora of the Brazilian delegation called attention to similar occurrences in Brazil.

Again, opinions concerning the origin are unresolved. However, studies are in progress, particularly at Blind River where the Geological Survey of Canada is making a careful investigation of the new exposures as they become available in mining operations.

Although precise figures have not been released, the wealth of material presented to the conference indicates that the broad uranium province in the western United States which extends from New Mexico to North Dakota and includes substantial portions of eight States probably is the most productive source of uranium in the world today. Dodd (Conference Paper 474) indicates that at present 61 per cent of the uranium production is derived from the Morrison formation in the Colorado Plateau.

Studies by various workers of the United States Plateau area outline a comprehensive program which is devoted to the many aspects of uranium geology. Among the various subjects discussed are sedimentation features of uranium-bearing strata, the localization of uranium ores in channels, the location of buried channels, the occurrence in strata of different ages, structural controls, regional distribution, permeability of ore-bearing strata, fluid transmission in ore beds, the minerals involved in uranium emplacement, and the relationship of mineral suites to oxidation above water tables. Portions of this work were summarized by Dr. L. R. Page during the panel discussion.

Much information was released at the Conference on recent extensive investigations of marginal natural materials which could form large sources of uranium within the United States if required. These subcommercial sources include uranium-bearing black shale, low-grade lignite, uranium-bearing coal, and phosphate rock. The association of uranium with organic material, not only in shale, coal, and lignite, but in the sandstone impregnations of the Colorado Plateau area, is emphasized. The mechanism of emplacement, however, is not yet established completely. The extended studies of phosphate deposits indicate that small amounts of uranium which are distributed through widespread areas form a potential uranium by-product of phosphate production.

Among a number of contributions on uranium-bearing veins are the papers by various Canadian geologists as well as comments by Dr. A. H. Lang in the panel discussion. Recent uranium exploration of the Canadian Shield is reported to have moved southward from Great Bear Lake. During the conference it was announced that the Ace mine, just north of Lake Athabasca, was starting a daily production schedule of 2000 tons. Dr. M. Roubault described several productive uraninite-bearing veins which occur in France. The Belgian delegation's paper by Doctors Derriks and Vaes on the Shinkolobwe mine in the Belgian Congo indicates that this mine is operating at a depth of about 1150 feet, and in the lower workings unusual sulphide associations are being encountered. Here, the otherwise rare minerals of the pyrite group vaesite $(NiS)_2$ and cattierite

(CoS_2) are relatively common. Selenium also is present in unusual abundance.

The thorium deposits of India were discussed by Dr. D. N. Wadia (Conference Paper 875 and Panel Discussion). He indicated that the littoral of Travancore-Cochin contains over 1,000,000 tons of monazite and is a thorium asset of world importance. In this material ThO_2 is a constant constituent of the monazite to the extent of 8–10.5 per cent.

Two types of thorium occurrence were discussed: (1) occurrences in detrital sediments of either recent or ancient type, and (2) occurrences in crystalline rocks as veins or disseminations. Drs. J. H. Mackin and D. L. Schmidt (Conference Paper 305) outline the thorium-bearing minerals of the placer deposits of Idaho and correlate these placer accumulations with primary disseminated sources in the Idaho batholith.

A discussion of the mineralogy of thorium by Dr. Clifford Frondel (Conference Paper 302) points out that few essential thorium minerals are known compared with a large number in which uranium is an essential constituent. This may be attributed to a fundamental chemical difference as uranium apparently can be carried for considerable distances in solution before being deposited as secondary minerals. However, thorium is not transported and precipitated in the same way. It is interesting to note the absence of papers describing thorium deposits caused by secondary precipitation in contrast to the considerable number of papers on the precipitated uranium type as found on the Colorado Plateau.

Many additional features of interest could be mentioned although it is believed that even a brief résumé indicates the significance of the geological contributions of the conference. For the convenience of interested readers a complete list of the geological conference papers follows.

Conference Papers

Paper No.	*Author and Title*	*Country*
1	Lang, A. H., Uranium prospecting in Canada—ground and aerial surveys	Canada
14	Klepper, M. R., and Wyant, D. G., Uranium provinces	U.S.A.
15	Butler, A. P., Jr., and Schnabel, R. W., Distribution of uranium occurrences in the United States	U.S.A.
16	Neuerburg, G. J., Uranium in igneous rocks of the United States of America	U.S.A.
17	Larsen, E. S., Jr., Phair, G., Gottfried, D., and Smith, W. L., Uranium in magmatic differentiation	U.S.A.
18	Coats, R. R., Distribution of uranium and certain other trace elements in felsic volcanic rocks of Cenozoic age of the Western United States	U.S.A.
19	Sharp, B. J., Uranium deposits in volcanic rocks of the basin and range province	U.S.A.
20	Everhart, D. L., Uranium-bearing vein deposits in the United States	U.S.A.
21	Sims, E. K., and Tooker, E. W., Pitchblende deposits in the Central City District and adjoining areas, Gilpin and Clear Creek Counties, Colorado	U.S.A.
22	Becraft, G. E., Uranium deposits of the Boulder Batholith, Montana	U.S.A.
23	Staatz, M. H., and Osterwald, F. W., Uranium in the fluorspar deposits of the Thomas Range, Utah	U.S.A.
24	Adams, J. W., and Stugard, F., Jr., Wall-rock control of certain pitchblende deposits in Golden Gate Canyon, Jefferson County, Colorado	U.S.A.
25	Walker, G. W., and Osterwald, F. W., Relation of secondary uranium minerals to pitchblende-bearing veins at Marysvale, Piute County, Utah	U.S.A.
27	Thurlow, E. R., Uranium deposits at the contact of metasediments and granitic intrusives in the western United States	U.S.A.
28	Osterwald, F. W., Relation of tectonic elements in pre-Cambrian rocks to uranium deposits in the Cordilleran	U.S.A.

Paper No.	Author and Title	Country
	foreland of the western United States	
29	Kelley, V. C., Influence of regional structure and tectonic history upon the origin and distribution of uranium on the Colorado Plateau	U.S.A.
30	Wood, H. B., Age and environment of uranium host rocks in the United States	U.S.A.
32	Jobin, D. A., Regional transmissivity of the exposed sediments of the Colorado Plateau as related to the distribution of uranium deposits	U.S.A.
33	Phoenix, D. A., Relation of carnotite deposits to permeable rocks in the Morrison formation, Mesa County, Colorado	U.S.A.
34	Poole, F. G., and Williams, G. A., Direction of transportation of the sediment constituting the Triassic and associated formations of the Colorado Plateau	U.S.A.
35	Boardman, R. L., Ekren, E. B., and Bowers, H. E., Sedimentary features of upper sandstone lenses of the Salt Wash member and their relation to uranium-vanadium deposits in the Uravan District, Montrose County, Colorado	U.S.A.
36	Shawe, D. R., Significance of roll ore bodies in genesis of uranium-vanadium deposits on the Colorado Plateau	U.S.A.
37	Gabelman, J. W., Uranium deposits in limestone	U.S.A.
38	Hilpert, L. S., and Freeman, V. L., Guides to uranium deposits in the Gallup-Laguna area, New Mexico	U.S.A.
39	Isachsen, Y. W., Uranium deposits in the Shinarump conglomerate and Chinle formation on the Colorado Plateau	U.S.A.
40	Witkind, I. J., Channels and related swales at the base of the Shinarump conglomerate, Monument Valley, Arizona	U.S.A.
41	Keys, W. S., The Temple Mountain collapse, San Rafael Swell, Emery County, Utah	U.S.A.
42	Trites, A. F., Jr., Finnell, T. L., and Thaden, R. E., Uranium deposits in the White Canyon Area, San Juan County, Utah	U.S.A.
43	Carithers, W., Uranium deposits in shoreline sandstones of terrestrial and marine origin	U.S.A.
44	Davis, D. L., and Hetland, D. L., Uranium in clastic rocks of the Basin and Range Province	U.S.A.
45	Grutt, E. W., Uranium deposits in Tertiary clastics in Wyoming and Northern Colorado	U.S.A.
46	Sharp, W. N., McKeown, F. A., McKay, E. J., and White, A. M., Geology and uranium mineral deposits of the Pumpkin Buttes Area, Powder River Basin, Wyoming	U.S.A.
47	Bell, H., III, Gott, G. B., Post, E. V., Schnabel, R. W., and accompanying contributors, Lithologic, structural and geochemical controls of uranium deposition in the Southern Black Hills, South Dakota	U.S.A.
48	Shoemaker, E. M., Occurrence of uranium in diatremes on the Navajo-Hopi Reservation, Arizona, New Mexico and Utah	U.S.A.
49	Breger, I. A., and Deul, M., The organic geochemistry of uranium	U.S.A.
50	Gabelman, J. W., Uranium deposits in paludal black shales of the Dakota formation, San Juan Basin, New Mexico	U.S.A.
51	Swanson, V. E., Uranium in marine black shales of the United States	U.S.A.
52	Conant, L. C., Environment of accumulation of the Chattanooga shale	U.S.A.
53	Brown, A., Uranium in the Chattanooga shale of eastern Tennessee	U.S.A.
54	Mapel, W. J., Uraniferous black shales in the Northern Rocky Mountains and Great Plains regions	U.S.A.

Paper No.	Author and Title	Country
55	Vine, J. D., Uranium-bearing coal in the United States	U.S.A.
56	Masursky, H., Trace elements in coal in the Red Desert, Wyoming	U.S.A.
57	Denson, N. M., and Gill, J. R., Uranium-bearing lignite and its relation to volcanic tuffs in eastern Montana and the Dakotas	U.S.A.
126	Guimaraes, D., The areas of geologically probable occurrences of uranium and thorium in Brazil	Brazil
127	de Morais, L. J., Known occurrences of uranium and thorium in Brazil	Brazil
130	White, M. G., Távora, E., and Colab, The occurrence of uranium associated with auriferous conglomerate in the Serra de Jacobina, Bahia, Brazil	Brazil
131	Guimaraes, D., and Colab, The stano-tantalo-uraniferous deposits and occurrences in the region of S. Joao del Rei, Minas Gerais, Brazil	Brazil
132	MacFadyen, D. A., and Guedes, S. V., Air survey applied to the search for radioactive minerals in Brazil	Brazil
285	Derzay, R. C., The Los Ochos uranium deposit	U.S.A.
286	King, J. W., Uranium in lignites of South Dakota	U.S.A.
287	Pipiringos, G. N., Uranium-bearing coal in the central part of the Great Divide Basin, Sweetwater County, Wyoming	U.S.A.
288	Hail, W. J., Jr., Myers, A. T., and Horr, A. C., Uranium in asphalt-bearing rocks	U.S.A.
289	Pierce, A. P., Mytton, J. W., and Gott, G. B., Radioactive elements and their daughter products in the Texas Panhandle and other oil and gas fields in the United States	U.S.A.
290	McKelvey, V. E., Uranium in phosphate rock	U.S.A.
291	McKelvey, V. E., and Carswell, L. D., Uranium in the Phosphoria formation	U.S.A.
292	Altschuler, Z. S., Jaffe, E. B., Cuttitta, F., and accompanying contributors, The aluminum phosphate zone of the Bone Valley formation and its uranium deposits	U.S.A.
293	Cathcart, J. B., Distribution and occurrence of uranium in the calcium phosphate zone of the land-pebble phosphate district of Florida	U.S.A.
294	Bell, K. G., Uranium in precipitates and evaporites	U.S.A.
295	Weeks, A. D., Mineralogy and oxidation of the Colorado Plateau uranium ores	U.S.A.
296	Gruner, J. W., A comparison of black uranium ores in Utah, New Mexico and Wyoming	U.S.A.
297	Laverty, R. A., and Gross, E. B., Paragenetic studies of uranium deposits of the Colorado Plateau	U.S.A.
298	Stieff, L. R., and Stern, T. W., The interpretation of the $Pb^{206}/U^{238} < Pb^{207}/U^{235} \ll Pb^{207}/Pb^{206}$ age sequence of uranium ores	U.S.A.
299	Hoekstra, H. R., and Katz, J. J., Isotope geology of some uranium minerals	U.S.A.
300	McKelvey, V. E., Everhart, D. L., and Garrels, R. M., Summary of hypotheses of genesis of uranium deposits	U.S.A.
301	Twenhofel, W. S., and Buck, K. L., The geology of thorium deposits in the United States	U.S.A.
302	Frondel, C., The mineralogy of thorium	U.S.A.
303	Singewald, Q. D., and Brock, M. R., Thorium deposits in the Wet Mountains, Colorado	U.S.A.
304	Wallace, S. R., and Olson, J. C., Thorium in the Powderhorn District, Gunnison County, Colorado	U.S.A.
305	Mackin, J. H., and Schmidt, D. L., Uranium- and thorium-bearing minerals in placer deposits in Idaho	U.S.A.
306	Overstreet, W. C., Cuppels, N. P., and White, A. M., Monazite in the southeastern United States	U.S.A.

Paper No.	Author and Title	Country
307	Vickers, R. C., Geology and monazite content of the Goodrich quartzite, Palmer Area, Marquette County, Michigan	U.S.A.
328	Roubault, M., Les gisements d'uranium de la France métropolitaine et des territoires Français d'outre-mer	France
338	Lenoble, A., Methode de recherche et d'étude des gîtes uranifères	France
470	Johnson, J. C., Nuclear fuel for the World Power program	U.S.A.
471	Staffs of U. S. Geol. Survey and U. S. Atomic Energy Comm., Natural occurrence of uranium in the United States	U.S.A.
472	Finch, W. I., Uranium in terrestrial sedimentary rocks in the United States exclusive of the Colorado Plateau	U.S.A.
473	Fischer, R. P., Uranium-vanadium-copper deposits of the Colorado Plateau region	U.S.A.
474	Dodd, P. H., Examples of uranium deposits in the upper-Jurassic Morrison formation on the Colorado Plateau	U.S.A.
502	Kerr, P. F., Rock alteration criteria in the search for uranium	U.S.A.
503	Techniques for prospecting for uranium and thorium	U.S.A.
504	Page, L. R., Geologic prospecting for uranium and thorium	U.S.A.
505	Overstreet, W. C. *et al.*, Heavy-mineral prospecting	U.S.A.
506	Fix, P., Geochemical prospecting for uranium by sampling ground and surface waters	U.S.A.
507	Denson, N. M. *et al.*, Water sampling as a guide in the search for uranium deposits and its use in evaluating widespread volcanic units as potential source beds for uranium	U.S.A.
508	Lovering, T. S. *et al.*, The use of geochemical techniques and methods in prospecting for uranium	U.S.A.
509	Cannon, H. L., and Kleinhampl, F. J., Botanical methods of prospecting for uranium	U.S.A.
510	Boyle, T. L., Airborne radioactive surveys	U.S.A.
511	Stead, F. W., Instruments and techniques for measuring radioactivity in the field	U.S.A.
512	Comstock, S. S., Scintillation drill-hole logging	U.S.A.
513	Chester, J. W., Drilling technique in search of uranium	U.S.A.
514	Black, R. A., Geophysical exploration for uranium on the Colorado Plateau	U.S.A.
515	Denson, M. E., Geophysical-geochemical prospecting for uranium	U.S.A.
516	Pitman, R. K. *et al.*, Subsurface techniques for outlining favorable zones by widely spaced core drilling	U.S.A.
517	Wood, H. B., and Grundy, W. D., Techniques in exploration of Shinarump type channels on the Colorado Plateau	U.S.A.
625	Baranov, V. I., Aeroradiometric prospecting for uranium and thorium deposits and the interpretation of gamma anomalies	U.S.S.R.
626	Saukoff, A. A., Radiohydrogeological method in prospecting for uranium deposits	U.S.S.R.
629	Paley, P. N., Determination of small quantities of uranium in ores	U.S.S.R.
630	Golbek, G. R. *et al.*, The physical method of determining the content of uranium, radium and thorium in radioactive ores	U.S.S.R.
759	Davidson, C. F., The radioactive mineral resources of Great Britain	U.K.
760	Davidson, C. F., Radioactive minerals in the Central African Federation	U.K.
761	Davidson, C. F., Radioactive minerals in the British Colonies	U.K.
763	Bisby, H. *et al.*, Instrumental developments in the prospecting, mining and chemical processing of nuclear materials	U.K.

Paper No.	Author and Title	Country
764	Davidson, C. F., Methods of prospecting for uranium and thorium	U.K.
782	Svenke, E., The occurrence of uranium and thorium in Sweden	Sweden
850	Brown, H., The possibilities of securing long range supplies of uranium, thorium and other substances from igneous rocks	U.S.A.
865	Shen, J. T., Exploration of monazite and associated minerals in the province of Taiwan, China	China
869	Vohra, K. G., Remote location of uranium and thorium deposits	India
875	Wadia, D. N., Natural occurrences of uranium and thorium in India	India
887	Siggerud, T., On the occurrence of uranium and thorium in Norway	Norway
918	Ippolito, F., Present state of uranium surveys in Italy	Italy
956	Survey paper on the natural occurrences of uranium and thorium in Thailand	Thailand
963	Ristić, M., Deposits of uranium and thorium in Yugoslavia	Yugoslavia
968	Cavaca, R., Uranium prospection in Portugal	Portugal
980	Clemente, A., and Reyes, E., Uranium deposits in the Philippines	Philippines
999	Angelelli, V., Characteristics and distribution of the uranium deposits and findings in the Argentine Republic	Argentina
1000	Linares, E., El yacimiento Eva Perón, Malargué, Mendoza	Argentina
1001	Belluco, A., Las vetas de cuarzo uranífero del yacimiento "Presidente Peron," Mendoza	Argentina
1035	Huber, P., Uranium prospection in Switzerland	Switzerland
1036	Ministry of International Trade and Industry, Natural occurrence of uranium and thorium in Japan	Japan
1071	Commonwealth Dept. of National Development, Natural occurrence of U and Th	Australia
1073	Natural occurrence of uranium and thorium	Austria
1101	Report of the Atomic Energy Commission of Greece on uranium and thorium occurrence in Greece	Greece
1105	Derriks, J. J., and Vaes, J. F., Le gîte d'uranium de Shinkolobwe	Belgium
1114	Kerr, P. F., Natural occurrence of uranium and thorium	U. N.
1118	Yun, T. S., Occurrence of uranium and thorium in South Korea	Korea
1121	Cellini, R. F. *et al.*, Studies of Spanish radioactive minerals. Part I. Double phosphates of uranium-calcium and uranium-copper in veins of Gardeña (Córdoba)	Spain
1122	Medina, M. A., Radioactive deposits and possibilities in Spain	Spain
1129	Rahman, H., Prospects of finding radioactive mineral deposits in Pakistan	Pakistan

DEPT. GEOLOGY, COLUMBIA UNIVERSITY, NEW YORK, 27, N. Y.

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, OCTOBER 26, 1955

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 67, PP. 121-122 JANUARY 1956

DRAKENSBERG SCARP OF SOUTH AFRICA: A CLARIFICATION

BY LESTER C. KING

Several correspondents have written to me regarding a photograph of the Natal Drakensberg which was published in my paper on *Canons of landscape evolution* (King, 1953, Pl. 1, fig. 1). They note the horizontal basaltic lavas and inquire whether the photo does not demonstrate that the Drakensberg is structural rather than denudational in origin.

The Drakensberg of South Africa (Rogers, 1920, p. 25–33; King, 1944, p. 255–282) is fully 700 miles long, extending from Lat. 23°S. to Lat. 32°S. In this distance its crest, face, and foot traverse many geological formations of different types and ages. It begins near the Limpopo Valley in the north, where for 70 miles the whole scarp, together with the plateau country above and the low veld at its foot, consists of Archean gneisses and granites with occasional schist belts striking at an angle of about 70° with the range. There is no cap rock, and the scarp separates two cyclic denudational landscapes of different ages without any reference to bedrock structures. As the plateau surface above and the lowveld at the foot are bevelled horizontally by erosion without regard for bedrock, so the retreating scarp shows equal disregard for structure in the inclined position.

At the Wolkberg a change appears in the solid geology. The Black Reef quartzites of the Transvaal System come in from the west, and the crest of the scarp is capped by a resistant formation, greatly enhancing its boldness. Here a mighty wall overlooks the low veld to the east, barring easy passage to the interior, though gashed by canyons as much as 3000 feet deep (*e.g.*, Blyde River canyon; Olifants River gorge). Southward, the dip of the quartzite carries it down obliquely across the face, and the top is irregularly capped with the Dolomite formation of the Transvaal system, which in turn descends into the face of the scarp to be found upon the intermediate platform that here runs along the lower part of the scarp. This platform, standing at 3000 feet around Graskop and Sabie, is itself a remnant of mid-Cenozoic cyclic planation, and behind it the high mountains are built of rocks of the Pretoria series, alternating shales and quartzites with basic intrusive rocks making the crest from place to place. No single capping formation is here responsible for the mountains, the summits of which attain nearly 7000 feet above the sea.

Beyond Sabie the dip reverses, the beds rise to the southward, and the crest level declines so that the Dolomite and Black Reef series once more form the top of the scarp. The latter, at Duivel's Kantoor, exercises a profound caprock effect and makes great cliffs crowning the lower slopes of granite, and so the line of the Drakensberg continues for 40 or 50 miles, to near Carolina 250 miles from the commencement of the range.

At the latitude of Carolina a profound change takes place in the composition of the Drakensberg. Forming first a thin capping which thickens southward until it composes the whole face of the Drakensberg and extends down into the foreland is the Ecca series, part of the Karroo system. Most of the series consists of weak shales, quite unsuited as escarpment makers (Rogers, 1920, p. xxvi), and though there are coal measure sandstones in the middle Ecca they make no more prominent a scarp than do the shales. Though the beds dip gently, the Drakensberg in these regions owes nothing to structure. It is, as always, merely a retreating erosional scarp that is sited *pro-tem* where denudational agencies, and not rock structure, have decided.

For a distance by Piet Retief the Drakensberg loses its wall-like aspect and throws great spurs forward to the east, making a promontory of dissected spurs and ridges between the deep valleys of the Usutu and Pongola rivers, but this change is merely local. The southern flank of the promontory, now formed wholly of Ecca series, is steep and straight, though aligned east and west (the Belelasberg) to Laing's Nek.

At Laing's Nek where the railway from Durban to Johannesburg passes over, the Drakens-

berg stands relatively low, only a little over 5000 feet, though residual mountains such as Majuba and Inkwelo overtop it by 1500 feet. Evidence of the retreat of the Drakensberg is here afforded by the striking capture of the Slang Spruit belonging to the plateau drainage by the head of the Buffalo River, part of the coastwise drainage. Beheading of the plateau drainage by retreat of the scarp is, indeed, common all along the Berg.

From Laing's Nek the appearance of the Berg does not alter much for 80 miles, for the cyclic planations above and below remain the same. Its rock composition alters, however. The several subdivisions of first the Ecca then the Beaufort series, comprising many thousands of feet of strata, shales, and sandstones with intrusive sheets of dolerite, successively pass athwart the face from the crest obliquely down to the foot as the scarp transects the regional structure of the great basin of the Karroo system. By Oliviershoek Pass the upper Beaufort makes the plateau crest line, with super-added mountains capped by Cave sandstone standing 1000 feet above the plateau near its edge (*e.g.*, van Rensburg's Kop). Still the crest of the Drakensberg scarcely attains 6000 feet, but a great change is in sight. A short distance south of Oliviershoek Pass the scarp encounters the great cake of early Jurassic basaltic lavas (4500 feet thick) that builds Basutoland. The clash of continental scarp and 10,000 feet high plateau produces the most magnificent part of the Drakensberg, between Royal National Park and the Cape Province. For 100 miles, not a road, and scarcely a track, crosses the range. The first road that does so, at Naude's Nek, climbs to 8300 feet. The lavas enhance the grandeur of this section of the Drakensberg, but they do not cause the Berg, nor do they control it. The Berg is master, and, under erosion, decides its own position, not the lavas. It would, indeed, be there without the lavas.

When the lavas end, at Xalanga Peak 250 miles from Royal National Park, the Drakensberg continues, less magnificent but holding its line as surely, separating the interior plateau of South Africa from the marginal regions as the Cave sandstone, Red Beds, and Molteno beds successively form the summit to Bamboes Berg, beyond which the Beaufort series builds the scarp.

Here at the Great Fish River the Great Escarpment turns westward to continue up the western side of Africa almost to the Congo River. Through this distance also it transects impartially all the rock series encountered.

So the Drakensberg is entirely independent of structure and transects in its course practically every major rock system of South Africa, involving perhaps 40,000 feet of different formations. Separating the high interior plateau of South Africa from the denudationally lowered marginal regions, it is wholly denudational, even to most of the details, and is part of the Great Escarpment which, from Southern Rhodesia, around the Union of South Africa to South-West Africa and Angola, forms everywhere a uniform feature, perhaps the most important single feature of the geomorphology for a distance of 2800 miles.

As this is so, the present position of the Drakensberg—governed wholly by scarp retreat—is clearly a temporary one, as the numerous river captures in different stages testify. Where and when did the Drakensberg originate? This question can be answered precisely (King, 1953, p. 746; 1944). It began as the coastal monocline of Natal, initiated, according to Du Toit (1954, p. 70), in the early Jurassic, and certainly not later than late Jurassic. Upon this flexure a denudational scarp soon developed, dividing the high interior from the littoral. Under erosive agencies it has continued to retreat with supreme indifference to type of rock terrain. It is doing so today, just as steep and as active as ever it was; after 120 million years and 150 miles of retreat it still makes a mountain wall.

References Cited

King, Lester C., 1944, Geomorphology of the Natal Drakensberg: Geol. Soc. South Africa Trans., v. 47, p. 255–282.

——1953, Canons of landscape evolution: Geol. Soc. America Bull., v. 64, p. 721–752.

Rogers, A. W., 1920, Origin of the Great Escarpment: Geol. Soc. South Africa Proc., v. 23, p. 25–33.

du Toit, A. L., 1954, The Geology of South Afrca: Oliver & Boyd, 3d ed.

UNIVERSITY OF NATAL, DURBAN, SOUTH AFRICA
MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, AUGUST 22, 1955

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 67, PP. 123-124 JANUARY 1956

LEAD AND SULFUR ISOTOPIC ABUNDANCES IN MISSISSIPPI VALLEY GALENAS

BY J. L. KULP, G. L. BATE, W. U. AULT, AND H. W. FEELY

A recent world-wide survey of the isotopic composition of lead from galena specimens (Bate and Kulp, in press) showed that the Mississippi Valley lead ores exhibit unusually large variations. The ratio Pb^{207}/Pb^{206} varied as much as 15 per cent in one district (Southeast Missouri), while all districts showed at least 5 per cent spread. The most likely explanation of these differences appears to be changes, either with time or place, in the source of the lead carried by the ore-forming fluids. An alternative hypothesis would be that the differences are due to isotopic fractionation during the transportation or deposition processes.

If isotopic fractionation occurred the sulfide accompanying the lead should have been fractionated to a much greater extent than the lead. Therefore, the second hypothesis might be proved or disproved by an isotopic study of the sulfur in the same galenas from which the lead had been analyzed. Table 1 compares the S^{32}/S^{34} ratio with the Pb^{207}/Pb^{206} ratio for samples of galena from the Illinois-Iowa-Wisconsin, Joplin, and Southeast Missouri districts. It is evident that for the first two districts the S^{32}/S^{34} is essentially constant and in the latter varies only by 2.7 per cent maximum while the Pb^{207}/Pb^{206} varies by 15 per cent.

It is concluded that isotopic fractionation is not important in causing the variation in the lead isotopes for these galena samples. This conclusion makes it possible to focus attention on the variable source of the leads. There must have been (1) several independent sources, or (2) a source which changed with time. Detailed examination of the isotopic variation in a complex lead ore district should permit discrimination between these possibilities. If a single source is involved the direction of change in the Pb^{207}/Pb^{206} ratio will help define the process of ore-fluid formation. Such a study is being initiated on samples from the Southeast Missouri District.

TABLE 1.—SULFUR AND LEAD ISOTOPIC RATIOS FOR GALENA FROM THE MISSISSIPPI VALLEY

Locality	S^{32}/S^{34}*	Pb^{207}/Pb^{206}
Illinois-Iowa-Wisconsin:		
1. California Mine Cuba City, Wis.	22.04±0.3	.755
2. Galena, Ill.	22.15	.734
3. Dubuque, Iowa	22.13	.731
4. Hunt's Diggings near Dubuque, Iowa	22.19	.726
5. Hazel Green, Wis.	21.88	.717
6. Hazel Green, Wis.	22.00±.03	.711
Joplin District:		
8. Joplin, Mo.	22.21	.811
8. See Sah Mine, Okla.	22.29	.738
9. Southwestern Mo. Galena in Cannel Coal	22.26	.731
10. Jopkin, Mo.	22.23	.722
11. Joplin, Mo.	22.37	.717
12. Joplin, Mo.	22.39	.710
Southeastern Missouri District:		
13. Federal Lead Co. Flat River Jig Concentrates	21.80±.02	.837
14. St. Joe Mine Bonneterre	21.85	.786
15. Central Mine Flat River	21.89	.770
16. Mine LaMotte Madison Co.	22.07	.768
17. Columbia Lead Mine Flat River 4″ Galena Crystal	22.16	.729
18. Columbia Lead Mine Flat River opposite end of sample 17	22.15	.729
19. St. Joseph	22.40	.705

* Probable error ±.01 except where indicated
† Probable error ±.002

Reference Cited

Bate, G. L., and Kulp, J. L., In press, Lead isotope abundances in galenas, Econ. Geology

LAMONT GEOLOGICAL OBSERVATORY, PALISADES, N. Y.

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, SEPTEMBER 27, 1955
WORK SUPPORTED IN PART BY RESEARCH DIVISION, U. S. A. E. C.
LAMONT GEOLOGICAL OBSERVATORY CONTRIBUTION NO. 173

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 67, PP. 125-126 JANUARY 1956

TERMINOLOGY FOR STRATIFICATION IN SEDIMENTARY ROCKS

By John Bokman

Within recent months two notes (Ingram, 1954; Gray, 1955) have appeared suggesting modifications of the terminology for stratification of sedimentary rocks proposed by McKee and Weir (1953). In basing their classifications on thickness alone, however, all four authors have ignored the genetic aspect of stratification, upon which any sound description must ultimately rest.

The following brief summary of terms which have appeared in the literature has been made in order to determine the extent to which they may be applied to a genetic classification.

Otto (1938) has defined two basic units of stratification, the *lamina*, "the smallest recognizable unit layer of particles of a sediment," and the *sedimentation unit*, "that thickness of sediment which was deposited under essentially uniform physical conditions." Payne (1942, p. 1724–1726), introducing the criterion of thickness, has defined a *stratum* as "a layer, greater than 1 cm in thickness, that displays continuous (nondiscrete) variation in lithologic character. . . ." McKee and Weir (1953, p. 382), however, have defined the term in a purely qualitative sense as "a single layer of homogeneous or gradational lithology, deposited parallel to the original dip of the formation." Other qualitative and quantitative terms defined by them are *set*, *coset*, *bed* (a stratum greater than 1 cm thick), and *lamina* (a stratum less than 1 cm thick). Ingram (1954) has suggested that McKee and Weir's thickness classification of stratification and splitting be modified to fit a geometric scale, and Gray (1955) has pointed out that a bed, as they define it, must inevitably become a lamina as it thins to extinction.

It is clear, both from field observation and a reading of these papers, that the commonly used term bed in most instances refers to what Otto has termed a sedimentation unit, and that as such it should be the basic unit of any classification. The corresponding term in McKee and Weir's classification is probably stratum (or set). Where two lithologies alternate more or less regularly there is little difficulty in recognizing individual sedimentation units, but in a sequence of several consecutive sedimentation units of one lithology some difficulty may arise. The individual units may not be clearly differentiated, or where they are it may not be evident to what the separation is due. According to Otto (p. 578),

> "As long as the assignable causes of variation remain essentially constant or change slowly, the sediment deposited continuously during the shortest cycle of variation of these causes constitutes a sedimentation unit. However, if at some stage during the cycle of variation physical conditions undergo a definite change, such as from laminar to turbulent flow in a lake, this change marks a sedimentation-unit boundary. Also if sedimentation ceases locally or is replaced by erosion, the change records a sedimentation-unit boundary."

In the case of several consecutive units of the same lithology the physical conditions must have undergone only slight changes at each bedding plane. Where beds of different lithologies are adjacent the change was more marked. Even with this concept in mind it may occasionally be difficult to decide whether a particular group of stratification units should be called sedimentation units, particularly if they are quite thin.

A unit of stratification smaller than the sedimentation unit which is commonly observed in the field has been termed the lamina (Otto, 1938). Although McKee and Weir have placed a thickness connotation on it, it is preferable that there be none, as Gray has recognized that it may be laterally equivalent to the thicker "bed," and Otto (p. 575) has pointed out that "the thickness of a lamina may vary from microscopic size for clays to many inches for coarse gravel deposits." Also, whereas many sedimentation units are laminated others may be structureless. Parting or splitting is probably related to lamination and consequently may be irregular because it is controlled by "unassignable causes (Otto, 1938)."

McKee and Weir's term set (or coset) is applicable to the unit larger than the sedimentation unit—a group of several consecutive

sedimentation units of the same lithology, unseparated by units of a different lithology.

The genetic classification here proposed combines appropriate terms of the foregoing writers without, it is hoped, unduly distorting their original meanings.

Lamina—the smallest layer of particles recognizable in the sediment

Bed—that thickness of sediment which appears to have been deposited under essentially constant physical conditions

Set—a unit composed of two or more consecutive beds of the same lithology

Because of its wide usage the term bed has been retained in place of the more cumbersome "sedimentation unit." All three units may be referred to in a general sense as strata.

None of the terms defined carry any connotation of thickness. A thickness classification should be based on a geometric scale, as this type of grouping tends to normalize bed-thickness distributions (Pettijohn, 1949, p. 140). An adaptation of the familiar Wentworth scale of particle size (using cm instead of mm) is directly applicable to thickness measurements and seems preferable to the one proposed by Ingram (1954). Since it is based on multiples of the square root of 10 cm its class limits are only approximations of the true values, and too many classes below 1 cm and not enough above are provided.

Although it is desirable to set up a standard scale for the grouping of bed-thickness measurements the desirability of naming the classes so defined (*e.g.*, flaggy, thinly bedded) is questionable. Too many of the available terms have appeared in the literature in one or several other senses to hope for uniformity of usage.

The writer is indebted to Jack Young for a critical reading of the manuscript.

REFERENCES CITED

Gray, H. H., 1955, Thickness of bedding and parting in sedimentary rocks: Geol. Soc. America Bull., v. 66, p. 147–148

Ingram, R. L., 1954, Terminology for the thickness of stratification and parting units in sedimentary rocks: Geol. Soc. America Bull., v. 65, p. 937–938

McKee, E. D., and Weir, G. W., 1953, Terminology for stratification and cross-stratification in sedimentary rocks: Geol. Soc. America Bull., v. 64, p. 381–390

Otto, G. H., 1938, The sedimentation unit and its use in field sampling: Jour. Geology, v. 46, p. 569–582

Payne, T. G., 1942, Stratigraphical analysis and environmental reconstruction: Am. Assoc. Petroleum Geologists Bull., v. 26, p. 1697–1770

Pettijohn, F. J., 1949, Sedimentary rocks: N. Y., Harper & Bros., 526 p.

418 West Marshall, Tulsa, Okla.

Manuscript Received by the Secretary of the Society, March 14, 1955